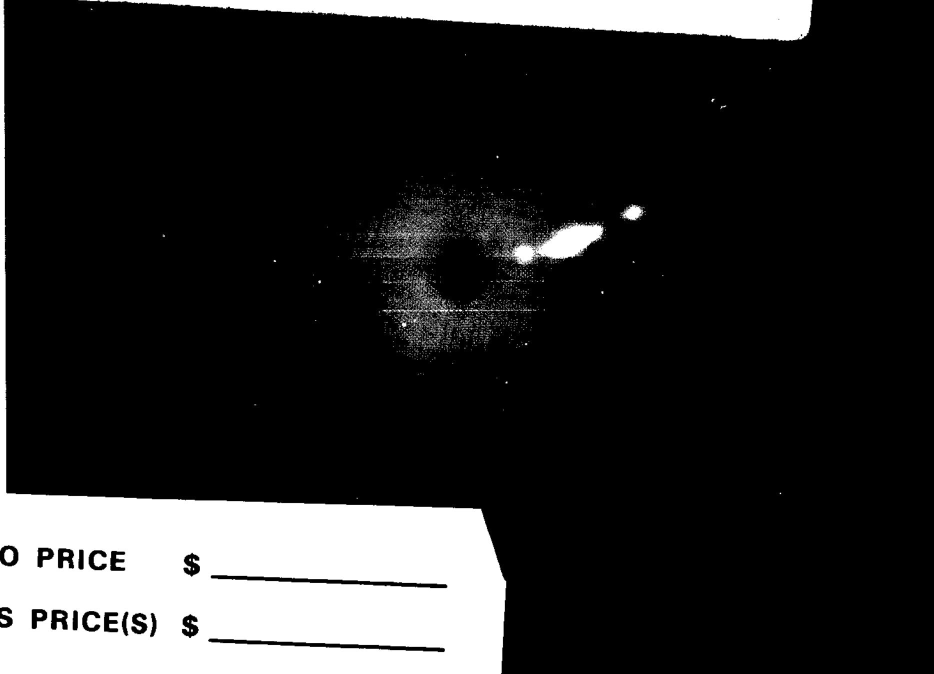
PHYSICS OF NONTHERMAL RADIO SOURCES



17

EDITED BY

Stephen P. Maran

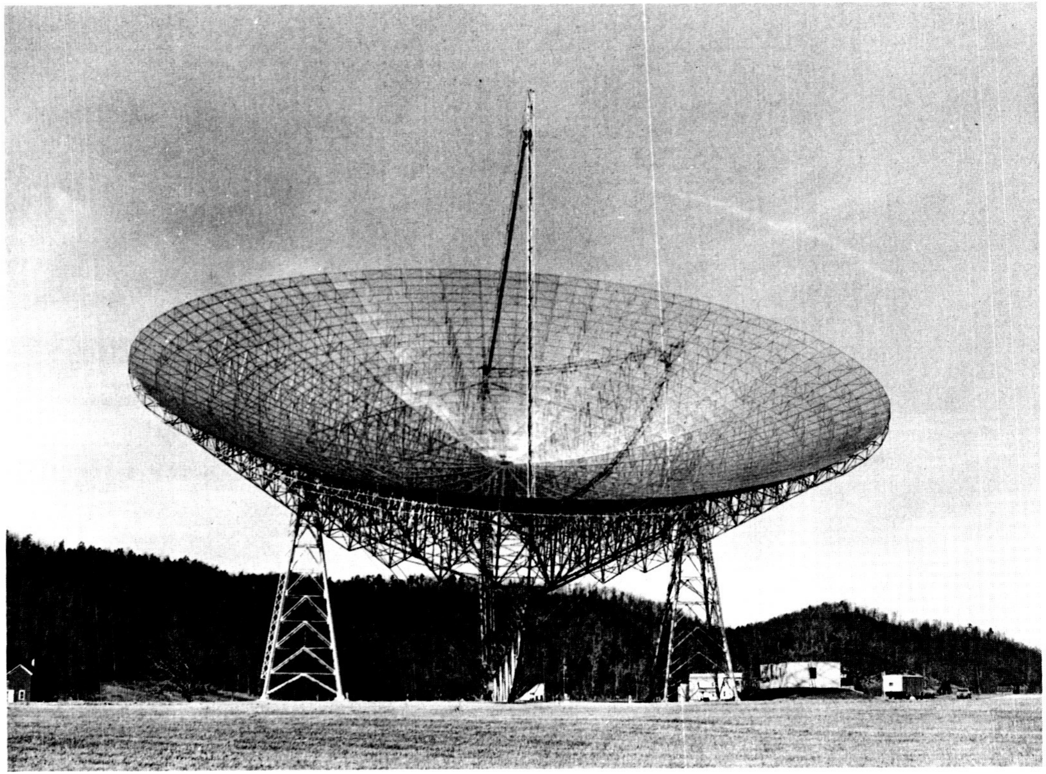
AND

A. G. W. Cameron

GODDARD INSTITUTE FOR SPACE STUDIES

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PHYSICS OF NONTHERMAL RADIO SOURCES



300-foot transit telescope at the National Radio Astronomy Observatory, Green Bank, West Virginia. (*Courtesy Dr. D. S. Heeschen.*)

PHYSICS OF NONTHERMAL RADIO SOURCES

NASA SP-46

EDITED BY

Stephen P. Maran

GODDARD INSTITUTE FOR SPACE STUDIES
and
DEPARTMENT OF ASTRONOMY
UNIVERSITY OF MICHIGAN

AND

A. G. W. Cameron

GODDARD INSTITUTE FOR SPACE STUDIES

GODDARD INSTITUTE FOR SPACE STUDIES
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JUNE 1964

COVER ILLUSTRATIONS

Front cover—

Artist R. Catinella's impression of the central region of Messier 87, giant elliptical galaxy in the Virgo Cluster (distance approximately 36 million light years), which has been identified as a strong source of radio emission. The famous "jet" emits optical synchrotron radiation.

Back cover—

An unusally broad dust lane is the most striking feature of the peculiar galaxy NGC 5128 (distance approximately 13 million light years), which has been identified with the strong radio source Centaurus A. (*McDonald Observatory*)

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price 75 cents

Table of Contents

Introduction

On December 3 and 4, 1962, the Goddard Institute for Space Studies, an office of the National Aeronautics and Space Administration, was host to an international group of astronomers and physicists who met to discuss the physics of nonthermal radio sources. This was the third in a continuing series of interdisciplinary meetings held at the Institute on topics which have a special bearing on the main lines of inquiry in the space program. The conference was organized by G. R. Burbidge of the University of California at San Diego and by L. Woltjer, then of the University of Leiden but temporarily at the Massachusetts Institute of Technology, and now of Columbia University.

Many nonthermal radio sources are of interest to astronomers, but only those outside the solar system were discussed at this conference. These latter sources comprise at least four types of object: supernova remnants within our galaxy, normal external galaxies, "radio galaxies," and certain objects which at that time were called "radio stars," but which are now known as "quasi-stellar radio sources." Objects in the last two categories are of particular interest to physicists because of their very large energy contents. It is a great challenge to determine how such vast quantities of energy can be generated in a short period of time and converted into the intense fluxes of relativistic electrons that are required to give the radio emission by the synchrotron process.

The sun emits 4×10^{33} ergs/sec over the entire spectrum. A typical supernova remnant has an emission rate of nearly the same order in the radio region alone. Further, there are unusual remnants, such as the Crab Nebula, which emit synchrotron radiation in the visible region at a rate which is an order of magnitude greater than the (thermal) solar value.

A normal galaxy will emit about 10^{44} ergs/sec of visible light and roughly 10^{34} ergs/sec in the radio region. The latter emission is believed to originate both in supernova remnants and in the general synchrotron radiation produced by fast electrons moving through the magnetic field structure of the object. But some galaxies (called "radio galaxies") are much stronger radio emitters. They produce 10^{40}–10^{45} ergs/sec at radio frequencies. In these cases, the radio source frequently comprises two principal components, whose separation may be $\sim 10^{6}$ light years. Lower limits to the ages of the sources are thus implied, and one can deduce that some of the most intense radio galaxies must have stored $\sim 10^{61}$ ergs in the magnetic field and high energy particles.

The energy required is equivalent to the total conversion of $\sim 10^{7}$ solar rest masses, and presumably is released in some event or series of events which occurs in the radio galaxy. However, there is no known process in which rest energy can be made totally available for such purposes. Thermonuclear reactions release about 1% of the rest energy, and it appears that probably only a few per cent of the rest energy of a massive collapsing star can go into a shock wave. Hence it appears that the actual matter involved in the violent processes which give rise to an intense radio galaxy must be of the order of 10^{8} to 10^{9} solar masses. Total galaxy masses are $\sim 10^{11}$ to 10^{12} $M_{\odot}$.

The puzzle of this large energy requirement was one of the principal motivations for the organization of the Dallas Symposium on Gravitational Collapse and Other Topics in Relativistic Astrophysics, held in December, 1963.

In the year between the conferences at the Goddard Institute and at Dallas, an immense amount of new observational material has been obtained regarding the quasi-stellar radio sources. In December, 1962, they were thought to be actual stars or supernova remnants, located in our own galaxy. By December, 1963, it had become virtually certain, however, that these objects are in fact located at extremely great distances. It had further been determined that these sources emit optically at a rate which far exceeds that of a galaxy, that their radio emission is comparable to that of the most intense radio galaxies, and that *they occupy volumes which are very small compared to that of a galaxy.* It may be that there is a continuous gradation of properties between the quasi-stellar sources and the intense radio galaxies. Because of the rapid obsolescence of the material presented on quasi-stellar radio sources at the Goddard Institute conference, it has been almost completely omitted from this volume. Readers are referred to the forthcoming proceedings of the Dallas Symposium and to the references listed elsewhere in this volume, for more information on these objects.

The papers in this book have been somewhat reorganized from their actual order of presentation at the Goddard Institute conference. Separate sections of radio observations, optical observations, and theory have been assembled, although there was some intermixture of the first two categories at the conference. It is evident that the immense strides which have been made in the understanding of radio sources have depended upon optical identifications of the radio objects, and these in turn have depended upon recent refinements in the determinations of the positions and structure of the radio sources, made possible by the use of large interferometers and (in a few cases) the lunar occultation technique. It is important that radio and optical studies should continue to be closely correlated in the future.

One of the most noteworthy observational advances has been the measurement of linear polarization in the radio radiation received from a number of extragalactic radio sources. Reports on this work by several observers present at the conference led to discussions concerning the Faraday rotation of the plane of polarization that would be consistent with the observations, together with the very interesting problem of whether this rotation is produced in our own galaxy, in the radio source itself, or in intergalactic space.

Another important aspect of radio sources is the variety of radio spectra which they exhibit. These variations, discussed at the conference, are undoubtedly associated with both the ages of the sources and the manner of production and loss of high energy electrons in them, but these relationships are not yet properly understood.

Significant *optical* properties of radio galaxies reported at the conference include the frequent occurrence of emission spectra which reveal the presence of excited gas with an unusual degree of turbulence. On direct photographs, such odd features as extremely bright central nuclei, filamentary structure, and "jets" have been found in some of the radio galaxies. In a few cases, optical polarization has been detected. Optical studies obviously have an important bearing on the development of theories to account for these objects.

The theoretical discussions at the conference were primarily concerned with two questions: (1) What is the source of energy for the radio emission? and (2) What model should be adopted for the magnetic fields and plasmas in the radio galaxies? It seems fair to comment that no reliable answers to these questions have yet been put forward, although the tentative ideas which have been advanced do have some very interesting aspects.

The general technique adopted for the preparation of these proceedings was as follows: A first draft of each speaker's remarks was prepared from a combination of the stenotypist's transcript and tape recordings made at the conference. After preliminary editing, these drafts were sent to the speakers, who corrected and (in some cases) updated them. We wish to thank the speak-

ers for their cooperation in this regard. The editors are grateful to Mr. George Goodstadt, whose painstaking care in the mechanical preparation of the proceedings is evident throughout this volume. We are also especially indebted to Mrs. Enid Silva, who did a fine job as Conference Secretary and also typed the draft material. Thanks are due to Mr. Raphael Kestenbaum, for the preparation of a number of the drafts. Several of the other Goddard Institute staff members gave valuable assistance with the conference arrangements and in the preparation of this volume; in the latter regard we are also grateful to Prof. William E. Howard III, Messrs. William A. Dent and Jerry R. Ehman, and several other astronomers at the University of Michigan.

A. G. W. CAMERON
Goddard Institute for Space Studies

S. P. MARAN*
Goddard Institute for Space Studies
and
Department of Astronomy
University of Michigan

* Present address: Kitt Peak National Observatory, Tucson, Arizona.

Radio Observations

A Survey of the Spectra of Radio Sources

R. G. Conway
NUFFIELD RADIO ASTRONOMY LABORATORIES
JODRELL BANK

N65 13252

The absence of spectral lines in nonthermal radio sources reduces one to measuring the continuous flux density S, defined in units of watts per square meter per cycle-per-second, at different frequencies. A plot of flux density versus frequency will usually produce a fairly smooth curve. It is customary to describe the spectrum of a radio source in terms of the spectral index, α, defined by

$$S \sim f^{-\alpha}$$

where f is the frequency. By this convention, α is positive for nonthermal sources.

In 1957, Whitfield (*1*) showed that the scatter which then existed in the available flux density measurements was largely due to differences in the scale factors employed by the various observers. He adopted the technique of normalizing all measurements with respect to one source, Cassiopeia A, which had been measured absolutely at several frequencies. Table I lists the observers whose absolute measurements of Cas A were used in the present study.

These observations of Cas A (Table I) involved two different operations: calibration of the receiver against an absolute noise power emitted by a thermal load, and the use of an aerial of known gain. At the three higher frequencies the standard aerial

Table I

Frequency (Mc/s)	Observer
38	Long, Cambridge (in preparation)
400	Seeger, Leiden (1956) (*2*)
1400	Findlay, Green Bank (unpublished)
3200	Broten and Medd, Ottawa (1960) (*3*)

is a horn, but at 38 Mc/s, where a horn would be impractical, an array of four dipoles above an earth screen was used. Observations on the other frequencies used in this study were not absolutely calibrated, so that the first step was to put them onto the absolute scale.

Figure 1a shows the measurements which have been made on Cas A to date. Notice the scatter about a smooth curve shown by raw observations such as these; the data are much more consistent than were those available to Whitfield. Forcing these observations to fit the straight line defined by the absolute measurements enables the scales of flux density to be recalculated. Thus, the scatter in the spectra of three bright sources, Taurus A, Cygnus A and Virgo A, shown in Figure 1b, has been reduced, by application of the scale factors determined from the Cas A data. This small scatter illustrates the point that relative measurements can be made rather accurately. Note that Tau A and Vir A have straight-line spectra on this (log f, log S) plot, corresponding to simple power laws, while Cyg A has not. This result was also obtained by Whitfield. We have made an age correction on the assumption that the flux density of Cas A decreases at one percent per annum, independent of the frequency.

Recently (Conway, Kellermann and Long, 1963) (*4*), we have assembled results at a number of different frequencies, ranging from 38 to 3200 Mc/s, using observations made at Manchester, Cambridge and CalTech. Figure 2 lists the frequencies, types of equipment, beam sizes and interferometer spacings employed at the various observatories. Schematics of the antenna arrangements are drawn in the last column.

The Jodrell Bank data were taken with the 250-foot paraboloid. At CalTech, an interferometer consisting of the two 90-foot reflectors was employed, except at 3200 Mc/s, where a single dish was used. The Cambridge observations were made with a variety of equipment, including the four-element interferometer at 408 Mc/s, an aperture synthesis system at 38 Mc/s, and a two-element interferometer at 178 Mc/s.

Altogether our list contains 160 sources. Unfortunately, not every source was observed at all the frequencies. In particular, many sources were not observed at the highest frequency, 3200 Mc/s. Additional data have therefore been included in the present study, to increase the statistical sample. They are the observations of Goldstein at Harvard (*5*), and especially the 3000 Mc/s Green Bank results of Heeschen and Meredith (*6*). There are three areas of overlap, as follows:

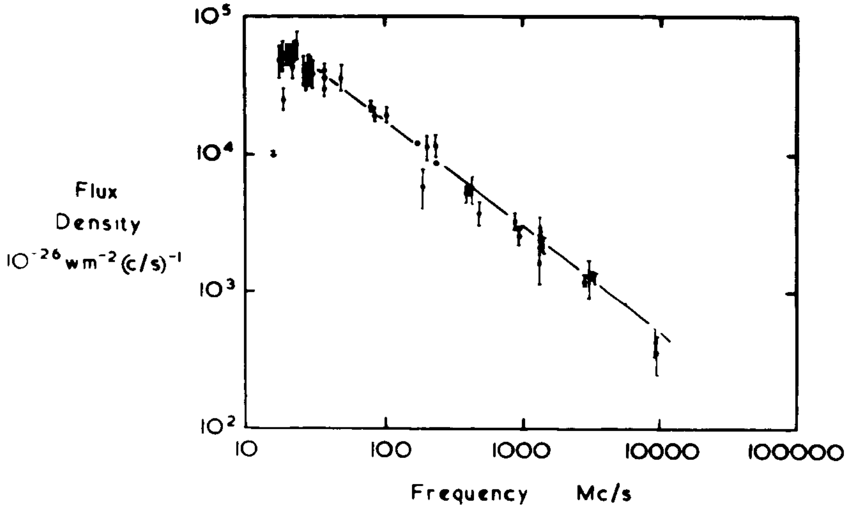


Figure 1a—Spectrum of Cassiopeia A.

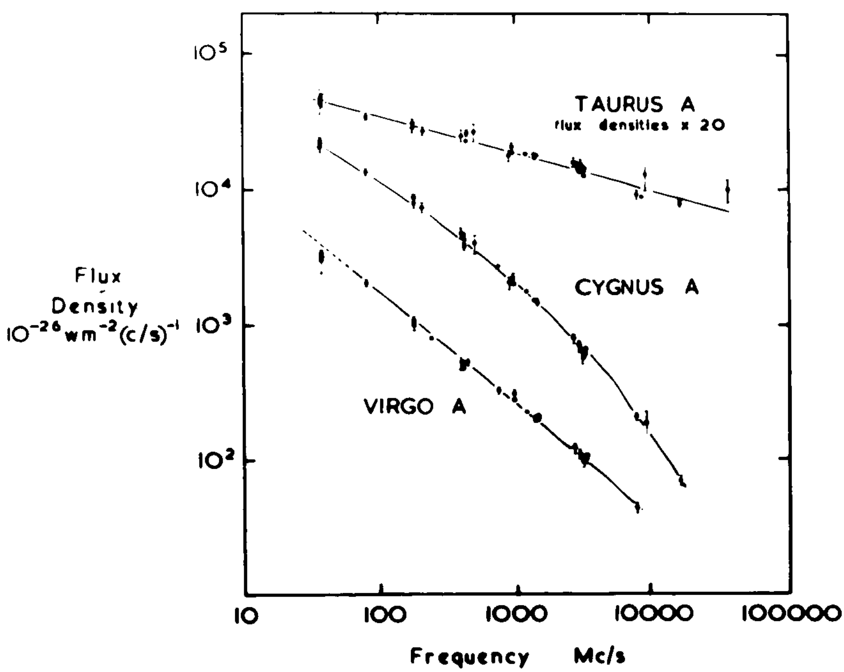


Figure 1b—Spectra of Taurus A, Virgo A and Cygnus A.

(1) 408 Mc/s—Cambridge observations
412 Mc/s—Manchester observations

(2) 1420 Mc/s—Harvard and CalTech observations

(3) 3000 Mc/s—Green Bank observations
3200 Mc/s—CalTech observations

In each of the three cases, the flux densities measured by different observers agreed extremely well.

Our two chief sources of error have been 1) corrections for source size (i.e.: If the source diameter is greater than 1′, a correction has to be applied to the interferometric data) and 2) confusion with adjacent sources. Observations made at the greatest interferometer spacing are the most sensitive to source size. Confusion has caused serious trouble in the past when large beam areas were used. Figure 2 shows that the effective beam areas were comparable at most frequencies over the wide spectral range of the present study.

The observations must be normalized. This was done at 38, 400 and 1420 Mc/s using the absolute measurements of the flux density of Cas A. We could of course have used Whitfield's

f	Obs.	System	Beam	Spacing	
38	CAM.	Pencil Beam	0°8 x 1°5	—	Aperture Synthesis
178	CAM.	P.B.& Int.	0°4 x 4°	470λ	
240	J.	P. B.	1.1	—	
408	CAM.	Int.	0°5 x 3°	70λ 787λ	
412	J.	P. B.	0°8	—	
710	C.T.	Int.	1°1	150λ	
958	C.T.	P.B.& Int.	0°8	200λ	
1420	C.T.	Int.	0°5	150λ	
3200	C.T.	P. B.	0°25	—	

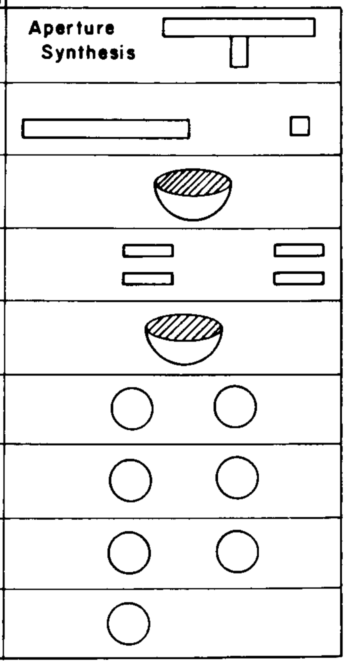


Figure 2—Schematics of equipment used at different frequencies.

method and obtained flux density scales at other frequencies by interpolating between these three frequencies, and normalizing the intensity of Cas A so as to fit a simple power law. However, we felt that Cas A was not the most suitable source to use for this interpolation, for three reasons. First of all, Cas A is a variable source. Its flux density is believed to decrease by about one per cent per annum, but it is not certain whether this variation is constant with frequency. Secondly, Cas A has a finite angular diameter, thus requiring a rather large correction at high interferometer spacings. Finally, its intensity is a factor of at least 100 over the majority of sources considered, and a factor of 1000 over the fainter sources. Determination of intensity ratios over such a great dynamic range would place great strain on the measurement of the receiver characteristics.

For the above reasons, we have avoided using Cas A as a standard source for interpolation and instead have normalized with respect to the seven sources whose spectra and 3C numbers are given in Figure 3. The method consisted of fitting a simple power law to the observations of each of the seven sources at 38, 408, 412, and 1420 Mc/s (for which absolute calibration was available) and defining the flux density scales at the other frequencies in the range 38-1420 Mc/s such that the observations of these seven sources would fall on the straight lines given by the power laws. Therefore, over the frequency range from 38 to 1420 Mc/s, the mean spectrum of the seven calibration sources is a straight line by definition. The flux density at 3200 Mc/s is absolutely calibrated and requires no scaling.

Using the scale factors determined in the above way, we obtained spectra for the 160 sources. Figure 4 consists of histograms of the spectral index so found, with sources at galactic latitudes $|b| > 10°$ considered in Fig. 4a, and those at lower latitudes included in Fig. 4b. In Fig. 4a, the spread in spectral index is approximately 0.2 about the mean value of 0.7. This agrees quite well with the conclusion of Harris and Roberts (7) who compared their 960 Mc/s measurements with the 159 Mc/s flux densities obtained in the 3C survey. This accord is to be expected, since we made use of the 960 Mc/s results, and furthermore our 178 Mc/s data were taken at the same observatory as the original 3C data.

The sources at low galactic latitudes show a greater spread in α than do those at high latitudes. One expects the former to be a combination of both galactic and extragalactic sources, so that their wider range of spectral index is not surprising. Further, we believe that the spread of 0.2 in the slopes of the high-latitude sources is a real effect, and not a result of instrumental limitations.

Observations taken at so many different frequencies make it possible to study the shape of the spectrum, and we find that there are definite differences between sources in this respect.

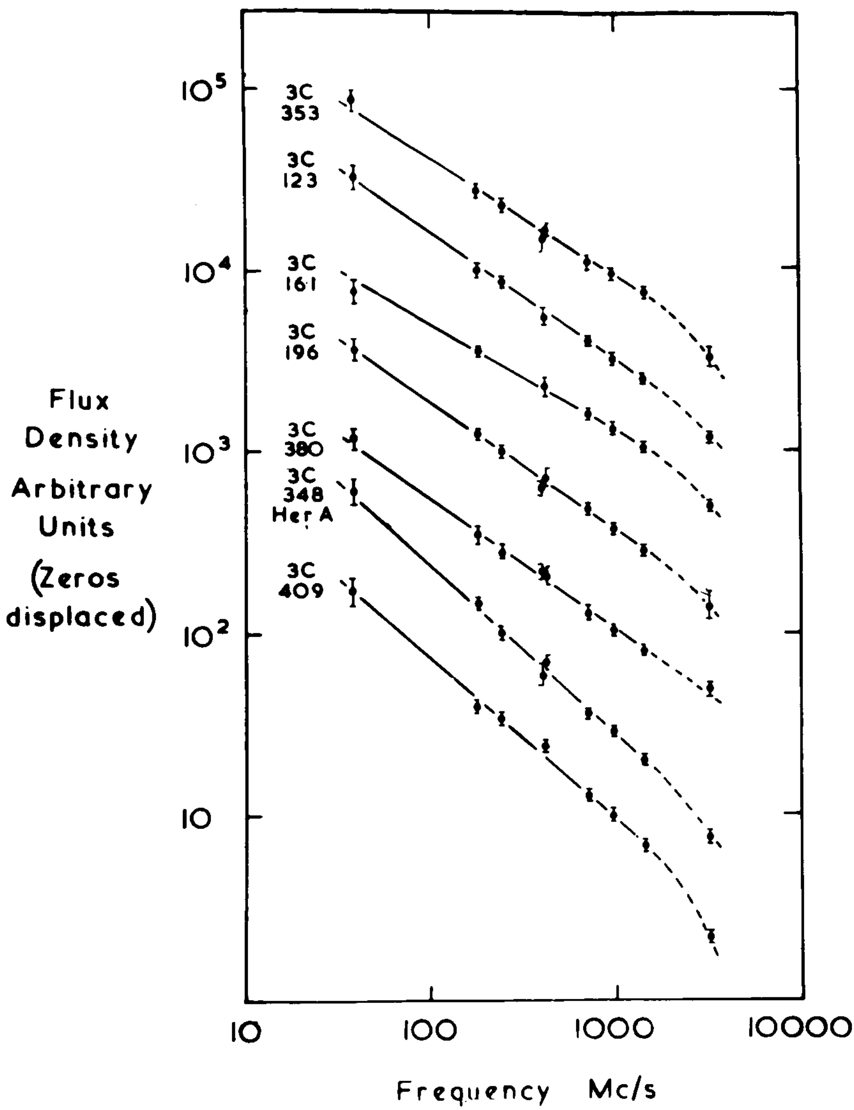


Figure 3—Spectra of seven calibration sources.

In particular, there are certain sources whose spectra are not straight lines, and we refer to them as class C. Examples of these curved spectra are shown in Figure 5. They include several sources identified with galaxies, as well as three sources identified with star-like objects: 3C 48, 147 and 286. Examples of source spectra which can be adequately represented by a straight line are given in Figure 6. The top four spectra in this figure are

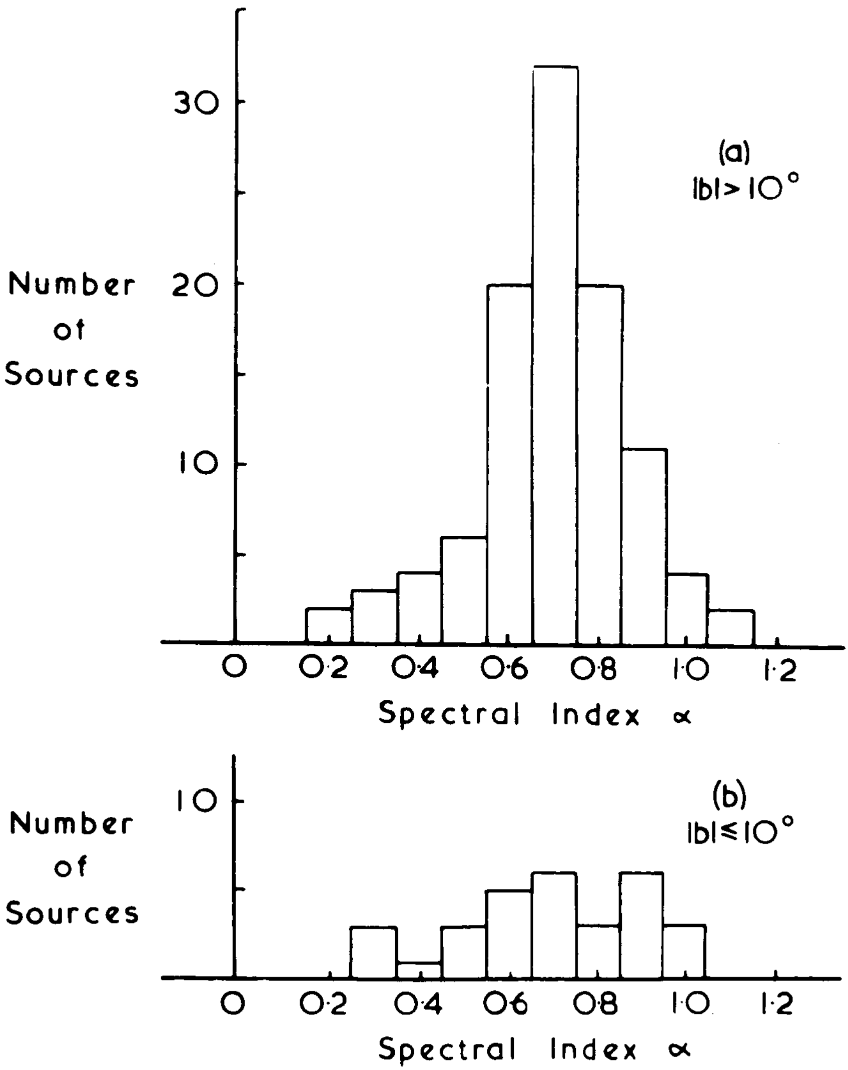


Figure 4—Spread in spectral index of nonthermal sources.

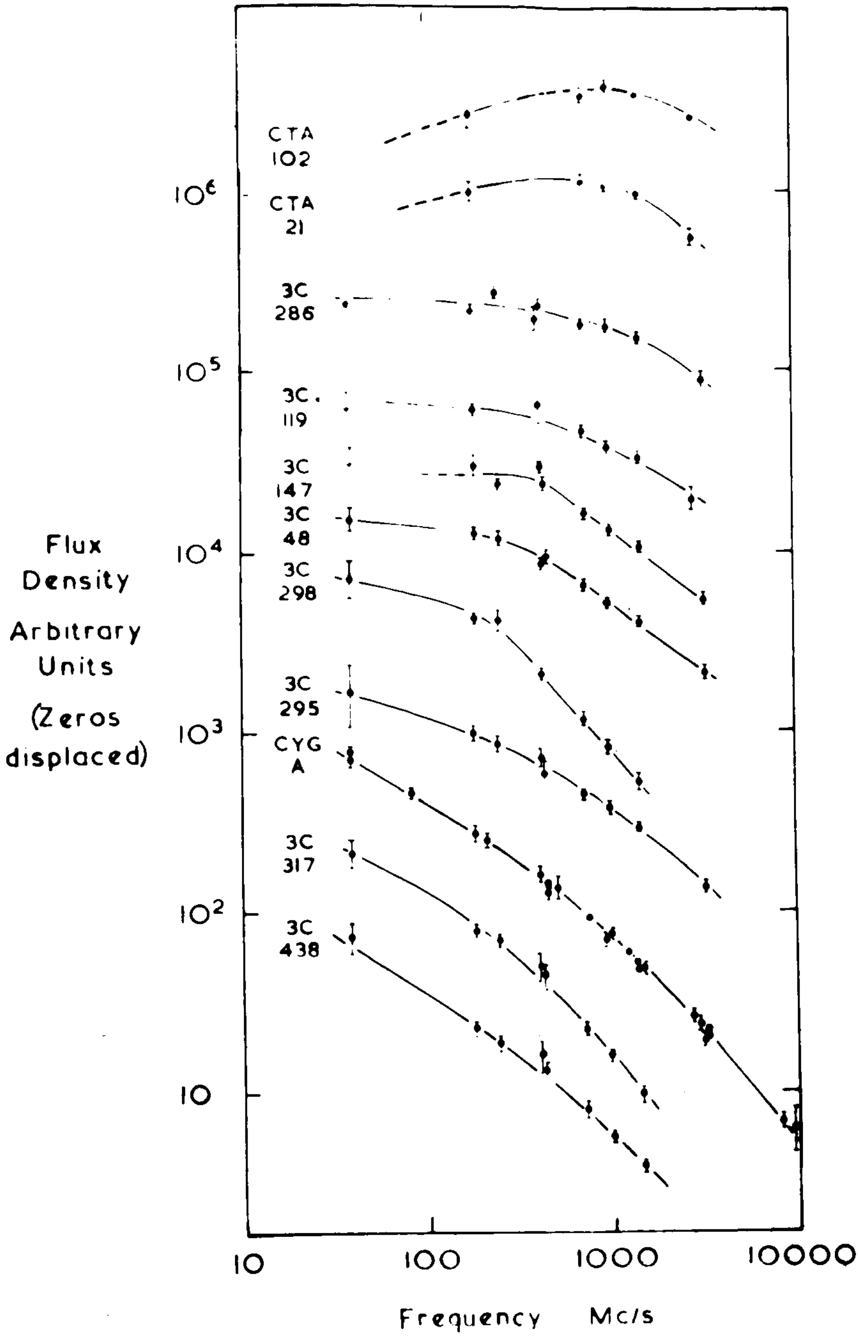


Figure 5—Spectra of the sources in class C.

straight all the way out to 3200 Mc/s. Among them is a supernova remnant, 3C 10. Two other supernova remnants, Cas A and Tau A, have straight spectra also. We denote these spectra, which are observed as straight out to 3200 Mc/s, as belonging to class S–1. There are a considerable number of sources, particularly among the fainter ones, whose measurements extend only to 1420 Mc/s. We classify such spectra as type S.

We have also found that a considerable number of sources have spectra which are straight out to 1420 Mc/s and then drop off toward higher frequencies, as shown in Figure 7. We have put these sources into another group, class S–2. Several of our

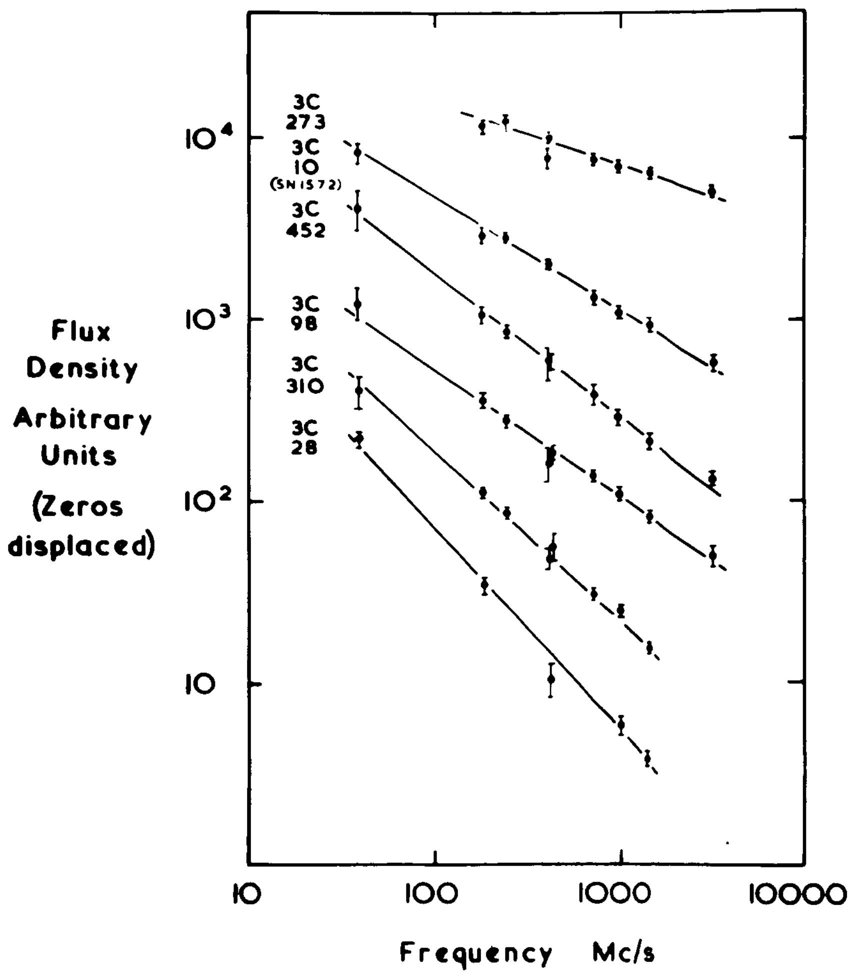


Figure 6—Spectra of a few sources of class S or S–1.

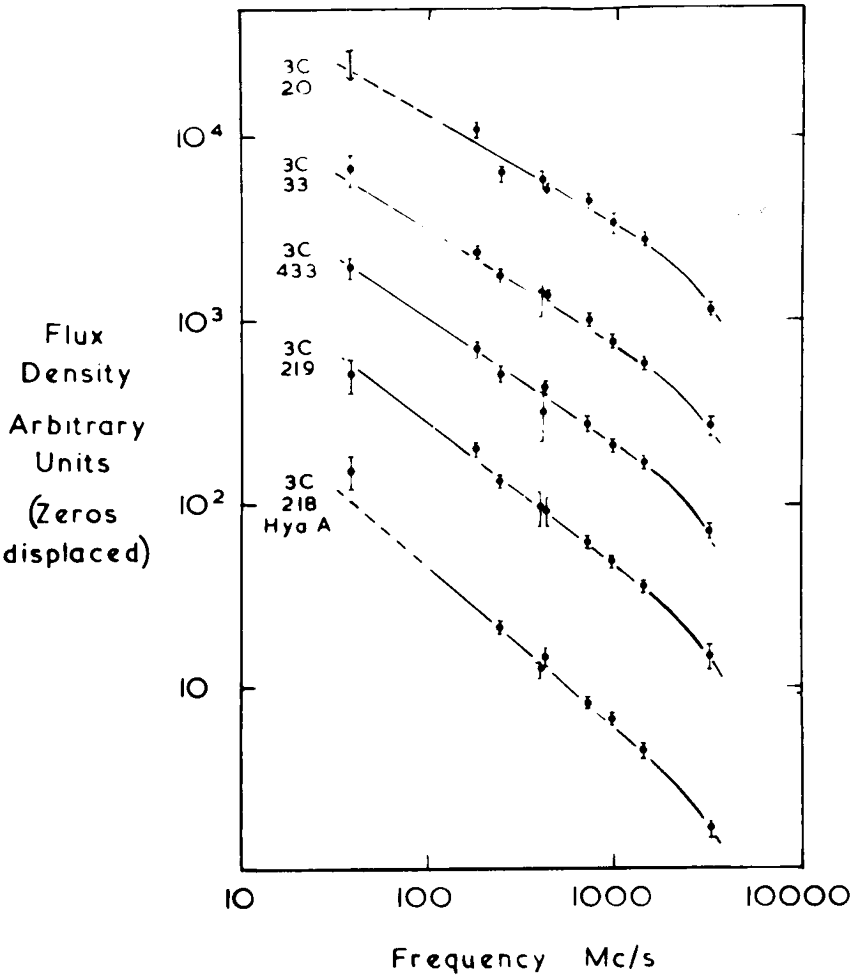


Figure 7—Spectra of a few sources of class S–2.

calibration sources are members of this class. We believe that this drop-off is a real effect and not due to experimental error.

In order to justify this separation into classes S–1 and S–2, we have calculated the deviation of the 3200 Mc/s point from the straight line obtained from the other points, and have defined a parameter ρ as the ratio of the extrapolated to the observed flux density at 3200 Mc/s. Figure 8, a histogram of the number of sources having each value of ρ, shows a peak at $\rho = 1$, corresponding to sources with straight spectra, and another peak sent individual sources. Each point is the mean of all the sources which lie in a given brightness range. The lines through the points represent RMS deviations from the means. There are altogether some 38 sources considered here. For the low brightness temperature sources, there is no significant spectral curvature, but for the highest class of brightness temperature there is appreciable curvature. This correlation has already been published by Kellermann, Long, Allen and Moran (1962) (*8*).

The above result can be interpreted in the following way. If the emission mechanism of these sources is the synchrotron process, then the spectral index must be related to the power law of the electron energy distribution. If the initial population of injected electrons can be expressed as

$$N\ (E) \sim E^{-\gamma}$$

where $\gamma = 2\ \alpha + 1$, the highest energy electrons will lose energy by radiation at the fastest rate, and a change of slope will develop in the electron energy distribution. The result is a curved radio spectrum, along which α changes by 0.5 over a decade in frequency. If the electron generation stops, a similar, but still more

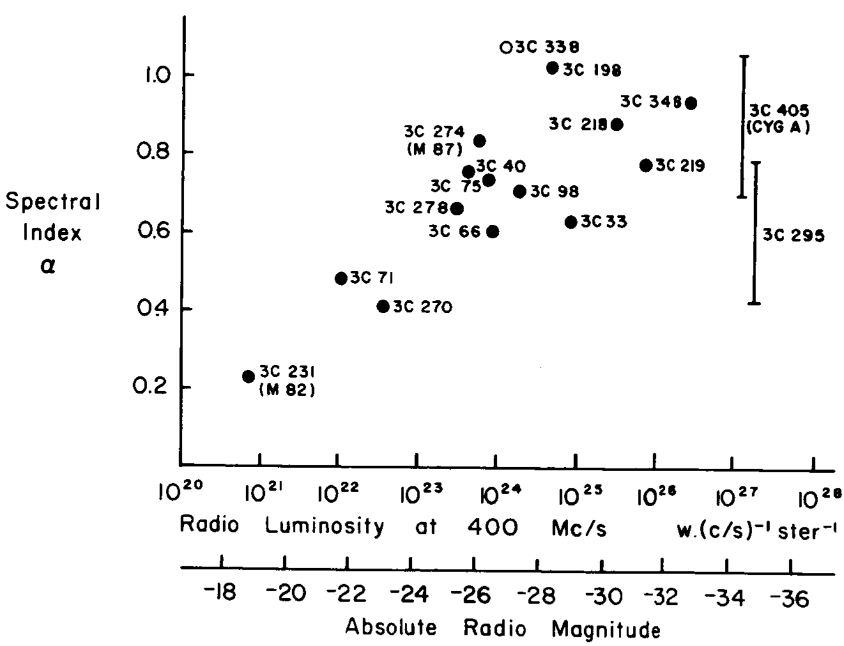


Figure 9—The spectral index and absolute magnitude of identified radio galaxies.

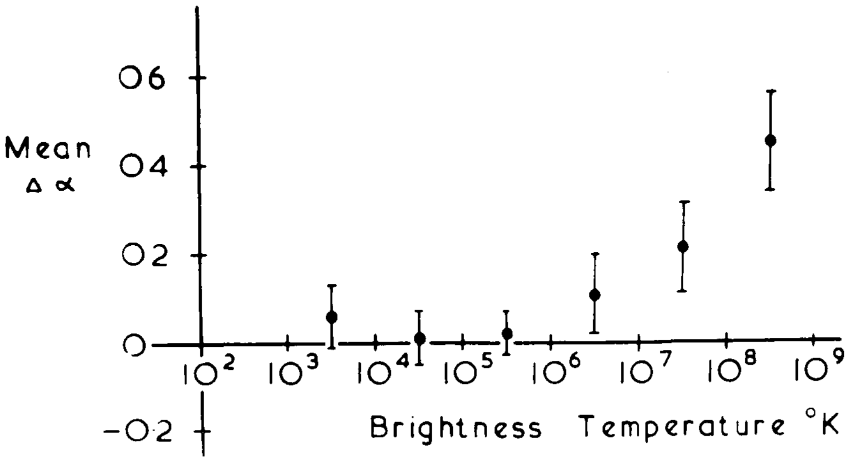


Figure 10.—The relation between the index of curvature $\Delta\alpha$ *and brightness temperature.*

marked effect occurs, and may result in a change in α of 1.0 or more.

The correlation of high brightness temperature with spectral curvature can thus be regarded as an age effect. The young sources, in which the magnetic field is presumably the highest, have the greatest synchrotron losses and develop this curvature. As time passes, the entire spectral diagram moves further to the left, and we observe an asymptotic spectrum. Because sources with $\Delta\ \alpha$ greater than 0.5 have been observed, we may say that in at least some radio sources the radiation must be longer lived than the process generating the relativistic electrons.

DISCUSSION

Woltjer: I have done a similar type of investigation with less data, on some 35 sources. Of course these were not my own observations, however I didn't find a definite indication for curvature in the spectrum at 3000 Mc/s. In my sample there were only three sources of your class C. How accurate are the 3000 Mc/s observations? There is, for example, a smaller beam width, which means that if the position isn't quite right, one is likely to measure a lower intensity.

Conway: I think that the best indication of the reality of the 3000 Mc/s data is the correlation between the independent measurements taken by Kellermann at CalTech and by Heeschen at Green

(A) *Supernovae*

We have considered four sources identified with supernova remnants, and found them all to be of class S–1. However, not all S–1 sources are supernova remnants.

(B) *Galaxies*

Thirty-five galaxies were observed and found to be distributed as shown in Table III. These results are not significantly different from those for the source list as a whole.

Figure 9 is a plot of the spectral indices of identified galaxies against absolute radio magnitude and absolute luminosity. There is a suggestion of correlation, as has been noted before, however it is not very good and in fact removal of one point (3C 231) would make Fig. 9 appear more like a scatter diagram. Another reason why we view this correlation with suspicion is that obviously a single value of α cannot be quoted for a class C source. Rather, the spectral index depends on frequency for such sources, and we have to quote a range for it. Clearly if the two lower values for 3C 295 and 405 in Fig. 9 are used, we have a rather different picture.

We searched for correlation among various other properties. In an effort to obtain a numerical parameter suitable for discussion, we took the observations and divided them into those at higher and those at lower frequencies. We then determined the mean straight-line slope for each of the two halves of the frequency range. Of course, there was no expectation that a spectrum might really consist of two straight lines; we simply wished to find an index of the curvature. Thus, we defined the curvature as $\Delta\,\alpha$, the difference between the spectral slope at 100 Mc/s and that at 1000 Mc/s. We find that the class C sources have a curvature of about 0.2, whereas the straight spectrum sources, of course, have a curvature of zero.

Figure 10 shows the correlation between $\Delta\,\alpha$ and the brightness temperature of the source at 160 Mc/s, as found from the present flux density measurements and the angular diameters obtained primarily at Jodrell Bank. The points in Figure 10 do not repre-

Table III

Class	Number
S	17
S–1	5
S–2	7
C	6

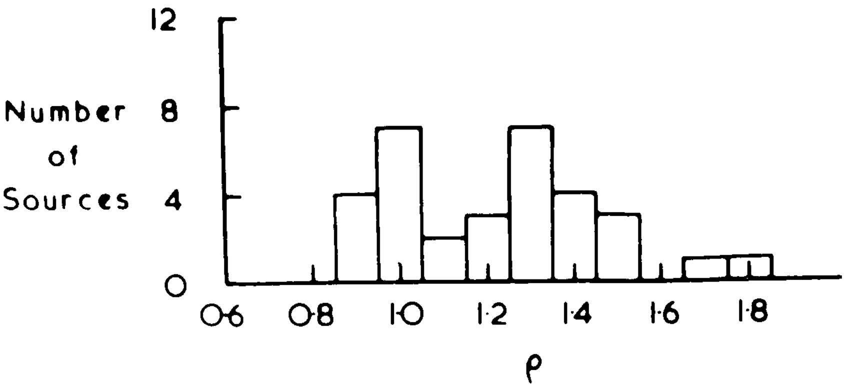


Figure 8—Distribution of the parameter ρ. The two peaks at 1.0 and 1.3 show the presence of two classes of source: S–1 and S–2.

corresponding to values of the 3200 Mc/s flux which are about 30 per cent lower than the expected values.

Of course, there may be systematic effects. In particular, the sources may be polarized at 3200 Mc/s, and since the original observations were taken in only one plane of polarization, errors may exist. But the polarizations which have been reported are only about 10 per cent, which is less than the 30 per cent deviation from the straight line which we find. Therefore, although we believe that the details of the 3200 Mc/s fluxes must be revised in the light of polarization results, we do not think that our general conclusions are vitiated by them.

Table II shows the distribution of our sources in the various spectral classes. Column 1 is the spectral class, column 2 gives the number of sources in each class according to our original analysis, and column 3 is an improved version of column 2, based on the addition of Heeschen's 3000 Mc/s data.

It is of interest to discuss the spectral characteristics of our sources in terms of the type of optical objects with which they are associated. Of course, definite identifications have not been made for most of the sources.

Table II

Class	Original Number	Revised Number
S	112	96
S–1	14	24
S–2	12	18
C	18	18

Bank. If the two sets of data are plotted against one another, there is of course a 5 per cent effect due to the fact that the frequencies are slightly different, but otherwise the points lie nicely along a straight line, with scatter (also of about five per cent) which can be expected from confusion and receiver effects. However, this scatter is much less than the 30 per cent deviation which we find and I think, therefore, that the drop-off at 3000 Mc/s is real. Our measurements were made on sources chosen from low frequency catalogues and therefore are subject to observational selection. There may actually be a higher proportion of such objects as CTA 21 and 102 (Figure 5) whose spectra appear to slope downward on either side of a frequency in the intermediate range, because such sources may have been missed in the frequency surveys due to their being too faint.

Minkowski: A southern source of that type has been observed at Parkes. It has about twice the flux density at 1400 Mc/s as at 400 Mc/s and it does not coincide with any optical object brighter than 19th magnitude.

Moffet: We have in progress at CalTech a survey at 1420 Mc/s of a limited region of the sky, in order to see show many more such objects may be found. We already know of one source which should have been detected in the revised 3C survey but was not. More of these can be expected.

Matthews: We have attempted to identify one of these sources, CTA 102, using the reasonably good radio position. Very close to the limit of an E plate taken with the 200-inch telescope, there is an object of about magnitude 21-22. I am not suggesting that this is actually the identification, but in any case, the source must be a very faint object, optically.

Roberts: Someone active in this field should propose a list of standard radio sources at an international meeting. This list should include some sources at low declinations, which could be observed from all locations, and should include many sources with straight spectra.

Crampin: Dr. Heeschen and I, in some theoretical work, were able to obtain a change of slope $\Delta\ \alpha$ above 0.53 for constant injection. If we had an injection cutoff, the spectrum dropped very steeply at the low frequency end.

van de Hulst: Can you make some comments about the possibility of attaining an appreciably higher precision in the near future?

Conway: The uncertainty in α is now fairly small. Nevertheless, only a small error in α will give rise to a very large effect in the curvature. At the moment say 100 sources have been determined at, say, seven frequencies to 10 per cent. Individual observatories may claim five per cent, but probably not better. I don't anticipate anyone getting much greater accuracy than this in the immediate future.

Woltjer: What is the prospect of getting good measurements at 8000 or 10,000 Mc/s where one should be able to see this curvature much more clearly?

Haddock: At the University of Michigan, we are observing 3C sources at 8000 Mc/s with a six-minute beam, and perhaps 20 to 30 flux densities will soon be available at this frequency.

Greenstein: It seems that extreme accuracy is unlikely to be obtained because of the non-uniform brightness distribution of some sources. Further, the polarization is almost certainly both frequency- and spatially-dependent. Basically, one has to employ a very narrow pencil beam, as well as take account of polarization.

Haddock: This is certainly true at $\lambda = 3$ cm, where an appreciable number of sources seem to be polarized. Because of this, we are redoing our observations with a polarimeter.

Conway: Polarization becomes fairly important at frequencies of 1400 Mc/s and higher. A comparison of the 160 Mc/s Jodrell Bank data with the 960 Mc/s CalTech measurements suggests that in most cases the brightness distribution of a source is not frequency-dependent, although there are a few examples where the reverse is true.

Moffet: The difficulty lies in measuring the total flux from an extended object which fades out gradually into the background. This problem is similar to that of measuring the optical magnitude of a galaxy.

Conway: If the brightness distribution is fairly constant across the source, the source can be defined as a given area. This area can then be observed at different frequencies; however the spectrum obtained by this approach may not necessarily refer to the whole object.

REFERENCES

(*1*) Whitfield, G. R. (1957), M.N.R.A.S. *117*, 680.
(*2*) Seeger, C. L. (1956), B.A.N. *13*, 100.
(*3*) Broten, N. W. and W. J. Medd (1960), Ap. J. *132*, 279.
(*4*) Conway, R. G., K. I. Kellermann and R. J. Long (1963), M.N.R.A.S. *125*, 261.
(*5*) Goldstein, S. J. (1962), A. J. *67*, 171.
(*6*) Heeschen, D. S. and B. L. Meredith (1961), Pub. N.R.A.O. *1*, 121.
(*7*) Harris, D. E. and J. A. Roberts (1960), P.A.S.P. *72*, 237.
(*8*) Kellermann, K. I., R. J. Long, L. R. Allen and M. Moran (1962), Nature *195*, 692.

Brightness Distributions in Nonthermal Radio Sources

Alan T. Moffet
OWENS VALLEY RADIO OBSERVATORY*
CALIFORNIA INSTITUTE OF TECHNOLOGY

An obvious goal for radio astronomy would be to obtain the same rich detail about the shape and structure of discrete radio sources as is contained in the best photographs of galactic nebulae or of external galaxies.

Where radio and optical objects are associated, we would like to compare the radio and optical pictures. Furthermore, a knowledge of the physical dimensions of a radio source makes possible an estimate of the physical conditions which give rise to the radio emission. As is the case in the optical domain, the "radio picture" might change when analyzed into various senses of polarization or when viewed at various wavelengths.

At present, we have a modest knowledge of brightness distributions in the larger-diameter sources. Our knowledge of the wavelength dependence of the brightness distributions is less extensive, and we know very little about the distribution of the polarized component of radio emission. I will summarize the presently available information on brightness distributions at wavelengths between 10 cm and 2 meters, neglecting polarization effects, which in this range are usually only a few per cent or less.

Radio measurements, like measurements on a photograph, are of *angular* dimensions. With such measurements alone, we are restricted to comparison of the appearance of various objects. Fruitful as this may be for purposes of classification, we would like to convert our angular measures to linear dimensions, and for this we need a measure of distance. As yet, there is no way of obtaining the distance to a radio source by radio means alone. All our knowledge of such distances has come from measurement of the redshifts of the associated optical objects. Wherever possible in the following remarks, I will speak in terms of linear

*Supported by the U.S. Office of Naval Research under contract Nonr 220(19).

dimensions, and I want to acknowledge at the outset our debt to those workers who have secured the optical identifications and distances which make such discussion possible.

METHODS

The most direct method for studying the structure of a radio source is to observe it with a pencil-beam antenna large enough to give the necessary resolving power. There are a few sources with sufficiently great angular extent so that they can be resolved with existing pencil-beam antennas. This method is straightforward and presents results which are easily interpreted; however, it has the disadvantages of limited resolution and occasional ambiguity in subtracting the background radiation, particularly at lower frequencies where the galactic emission is important. Present pencil beams have resolutions of, at best, a few minutes of arc. In the planning stage are pencil-beam instruments capable of resolving a minute of arc, and also telescopes with narrow fan beams of the order of ten seconds of arc. These will facilitate the study of a great many more of the smaller sources.

Recently, Hazard has introduced the use of lunar occultation observations to determine the brightness distributions of radio sources. This technique will undoubtedly be very valuable for those sources which lie in the moon's path. The maximum resolution is about one second of arc, limited by uncertainties in the contour of the moon's limb. A great advantage is that the very small effective beam area virtually eliminates the problem of confusion, which is almost always serious at the longer wavelengths. At shorter wavelengths, the method has the disadvantage that the nonthermal sources are weaker and the moon is much brighter.

Most of our information about the structure of nonthermal sources comes from interferometer investigations. The apparent intensity and position of a source, measured as functions of interferometer baseline length and orientation, give the amplitude and phase of the Fourier transform of the source brightness distribution. This transform may then be inverted in one way or another to recover the information we want. The spacing intervals at which one must observe a given source are governed by the sampling theorem. If the source is contained in an interval of X radians, it must be observed at spacing increments of no more than 1/X wavelengths. The resolution attained is about equal to half the width of the smallest fringe which is employed, *i.e.*, that corresponding to the longest spacing. Thus, a maximum spacing of 10,000λ corresponds to a resolution of about 10″.

The interferometer is most sensitive to the dominant features of a source. Thus a faint, large-diameter halo around a small source might easily be overlooked, as might small-diameter bright spots which contribute only a minor amount to the total radio intensity. Confusion, where several sources of comparable intensity are separated by about the width of the primary antenna beam, is difficult to sort out.

Table I summarizes three recent interferometric surveys which largely complement one another. A further extensive survey has been completed by Scheuer at Sydney, but the results have not yet been published.

Let me now go to a description of the various types of nonthermal sources, beginning with a brief discussion of those within our own Galaxy.

GALACTIC OBJECTS

Large Supernova Remnants

There is a group of galactic objects which we might call large supernova remnants, for instance IC 443, the Cygnus Loop or Puppis A. These have diameters from 15′ to several degrees, and may be resolved with pencil-beam instruments. Studies have been made by Mathewson, Large and Haslam at Jodrell Bank, and by Harris at CalTech, among others. Figure 1 shows Harris' con-

Table I

Three Major Studies of Source Brightness Distributions

			Number of Sources	
Observatory	Wavelength	Max. Baseline	"Galactic"	"Extragal."
Jodrell Bank[1]	1.9 m	61 000 λ EW	—	360
CalTech[2]	31 cm	1557 λ EW 1557 λ NS	21	174
Nancay[3]	21 cm	6950 λ EW 1820 λ NS	15	25

[1] Allen, L. R. *et al.* (1962), M.N.R.A.S. *124*, 477.
[2] Moffet, A. T. and P. Maltby (1962), Ap. J. Suppl. *7*, No. 67.
[3] Lequeux, J. (1962), Ann. d'Ap. *25*, 221.

Figure 1—Comparison of the radio and optical emission from the Cygnus Loop. Contours of antenna temperature (arbitrary scale) at 960 Mc/s. (From Harris.)

tours superposed on a photograph of the Cygnus Loop; it is quite typical of this type of object. There is a fairly circular distribution of emission suggesting a shell source, sometimes with ragged extensions, where the shell may have blown out. The diameter of the shell is typically 50 pc. Usually there are a few hot spots. The overall extent of the radio and optical objects is much the same, and the radio brightness distribution is not strongly dependent on wavelength. Typical peak brightness temperatures* range from 10 to 100°K.

*All brightness temperatures in this article will refer to a wavelength of 30 cm. The scaling factor is about $\lambda^{2.7}$ for a typical nonthermal source.

Small Supernova Remnants

Another group of galactic objects, which might be called small supernova remnants, includes for example Cas A, the Crab Nebula, and the remnants of Tycho's and Kepler's supernovae. There is undoubtedly a continuum of sizes, but there does seem to be a distinction in that the smaller objects are generally more regular and symmetrical. (Kepler's SN, which is quite complex, is an exception to this rule.) Cas A and Tycho's SN appear to be spherical shells, while the emission from the Crab Nebula is more concentrated towards its center.

Figure 2 shows a combination of the Nancay and CalTech results for Cas A, demonstrating its symmetrical nature. Brightness temperatures in Cas A are about 10^5 degrees and are nearly as great in the Crab. Other known objects in this group are much fainter. The structure does not change greatly with wavelength.

EXTRAGALACTIC SOURCES

Normal Galaxies

Turning now to sources of galactic dimensions, the information on brightness distributions in normal galaxies is rather sketchy and confusing. These objects have at best very low surface brightnesses; thus they are difficult to observe.

Based on long-wavelength studies of M31 and M33, Brown and Hazard proposed a model for emission from late-type spirals which consisted of a *disk* component with dimensions comparable to the optical disk of the galaxy, and a *halo* component of considerably greater extent. Figure 3 shows their observations of M31 at 158 Mc/s.

Short-wavelength observations by Lynds failed to detect the halo in M31, suggesting that the halo spectrum is steeper than that of the disk. However, recent studies by Mathewson and Rome of bright southern galaxies have shown that most of the emission comes from a region smaller than the optical disk. It would seem that the disk and halo model may be an oversimplification.

Brown and Hazard detected emission from irregular galaxies but found no sign of a halo component. Normal E and SO galaxies have not yet been detected at radio wavelengths.

Clearly, much more work needs to be done on normal galaxies. High-resolution observations at short wavelengths are made diffi-

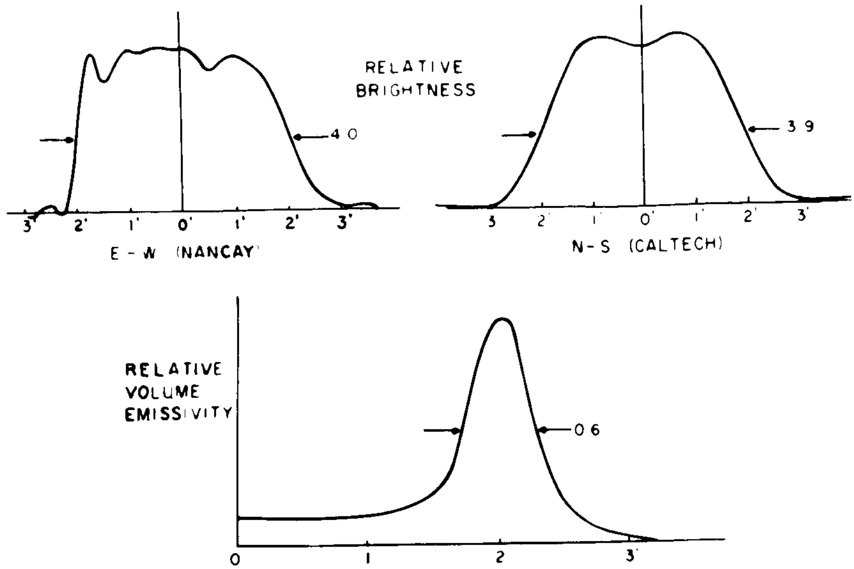


Figure 2—(top) East-West and North-South strip scans (of differing resolution) through Cassiopeia A. (bottom) Emissivity versus radius for a spherical shell model which could account for the observed strip scans. (After Lequeux.)

cult by the very low surface brightness of these objects—less than one degree in most cases. The spectral dependence of the various spatial components is of great importance in understanding the physics of the nonthermal emission. Studies of our own galaxy, carried out for the most part at Cambridge, have indicated that its spectrum is fairly complex, steepening at wavelengths shorter than about one meter.

Radio Galaxies

We may distinguish radio galaxies by their very high output of radio energy. No normal galaxy emits more than 10^{32} watts at radio wavelengths (10 Mc/s—10 Gc/s), while the more intense radio galaxies range up to 10^{37} watts. Figures 4-12 show several examples of the structure of radio galaxies. Except in Figures 5 and 6, where many contours are shown, only a rough indication of the shape of the radio emitting regions is given. Dashed contours should be regarded as quite uncertain. The numbers indicate relative intensities of the components, and the crosses indicate the uncertainties in placing the radio contours on the optical fields.

Cygnus A, as seen in Figure 4, is the preeminent example of a radio galaxy. The two components of the radio source are separated by about 100″ of arc, corresponding to 80 Kpc. Each component has a diameter of 20 Kpc. Observations by Lequeux show that at 21 cm there is a faint bridge of emission connecting the two components. The bridge is more prominent at longer wavelengths.

Fornax A, shown in Figure 5, and Centaurus A, in Figure 6, are the two radio galaxies of sufficiently large angular extent so

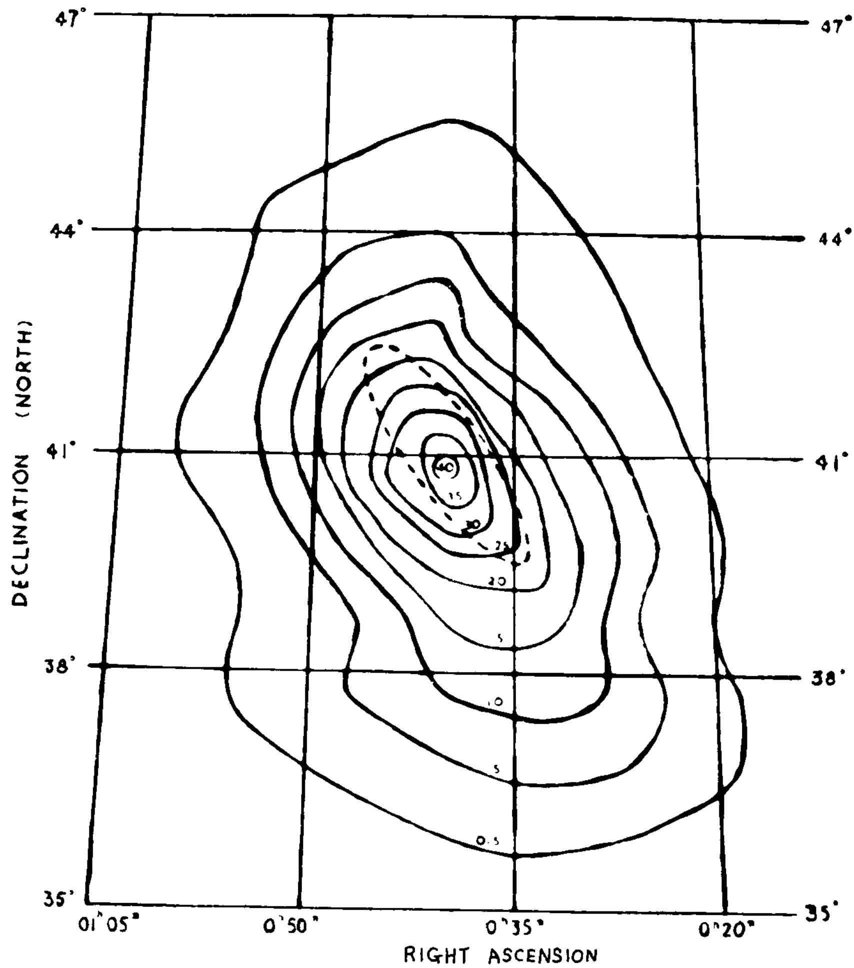


Figure 3—Isophotes of M 31 at 158 Mc/s with the background radiation removed. The contours are marked in arbitrary units of brightness temperature. The broken line shows the outline of the visible galaxy. (From Brown and Hazard.)

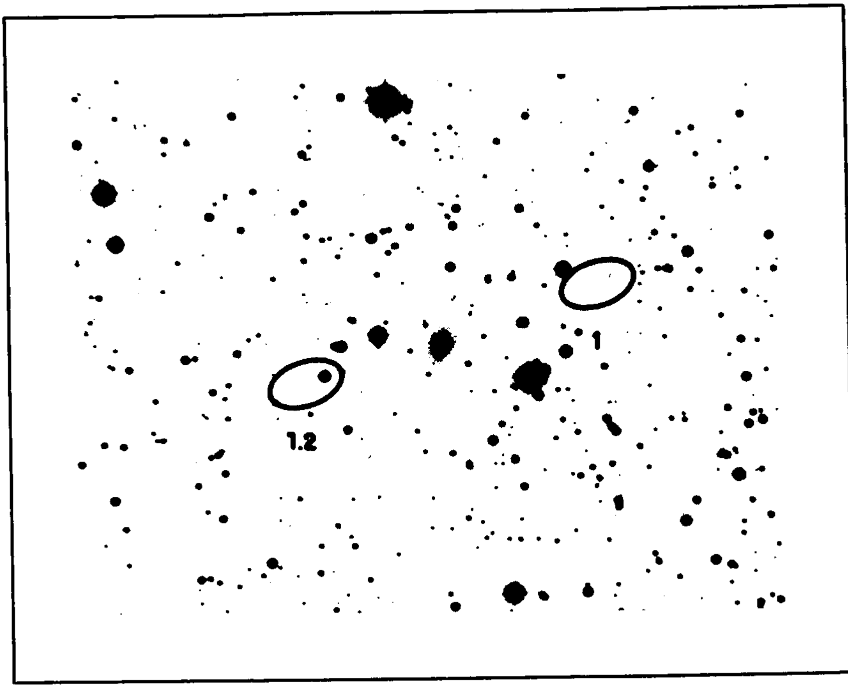


Figure 4—Approximate representation of the two radio components of Cygnus A superposed on an enlargement of a 200" plate by Baade. The numbers indicate the relative intensities of the components. North is toward the top and east toward the left.

that they have been resolved with pencil-beam antennas. Both show pronounced double structure extending to distances of more than 100 Kpc from the central galaxies. In addition, in the case of Centaurus A, there are a pair of bright components lying within the galaxy, separated in the plane of the sky by only 8 Kpc. These are shown schematically in the inset of Figure 6.

Other double sources are shown in Figures 7-10; however all sources do not display double structure. Figures 11 and 12 show two apparently simple radio sources. Another type of structure which shows up occasionally consists of an intense, small-diameter core superposed on a faint, extended halo. In these cases the spectrum of the halo is usually steeper than that of the core. Typical of these is 3C 274, where the core is associated with the jet seen in the center of the galaxy M 87. The radio halo in 3C 274 is somewhat larger than the galaxy.

Table II gives the classification into structural types of the sources Maltby and I observed at CalTech. Class E contains

Table II

Classification of 174 Extragalactic Sources Observed at 958 Mc/s

Classification	E	U	H	S	Total of Resolved Sources	N	Total of All Sources
Observed with Two baselines	11	24	6	4	45	45	90
Observed with only one baseline	4	16	1	9	30	54	84
Total observed	15	40	7	13	75	99	174

double sources having components of nearly equal intensities, Class U, those with unequal components. Class H contains the core-and-halo objects, and class S, the apparently simple sources. Those in group N were not resolved by our longest baseline (1557λ). It is clear that almost all the resolved sources show

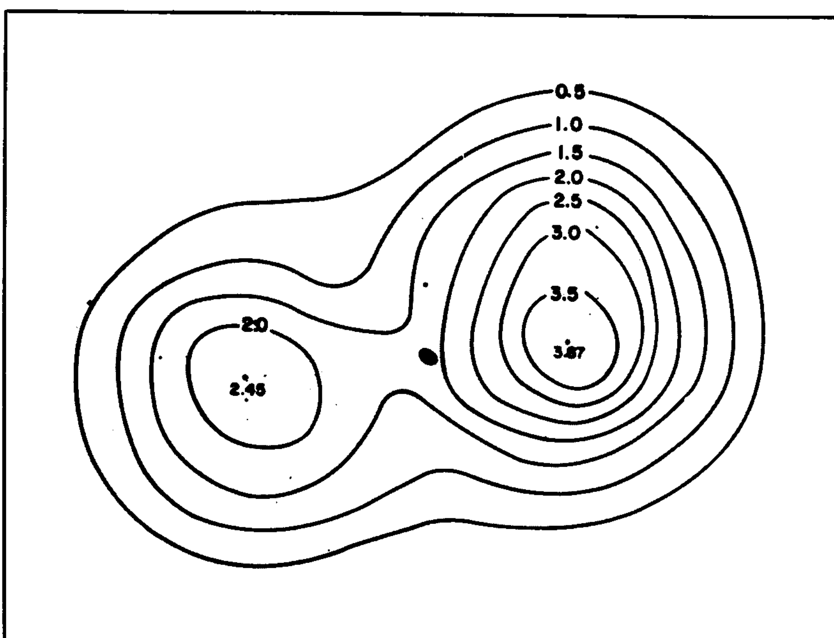


Figure 5—Contours of Fornax A (from a 10 cm study by Wade) superposed on the optical field (from a 48" plate by Zwicky). The central galaxy is NGC 1316.

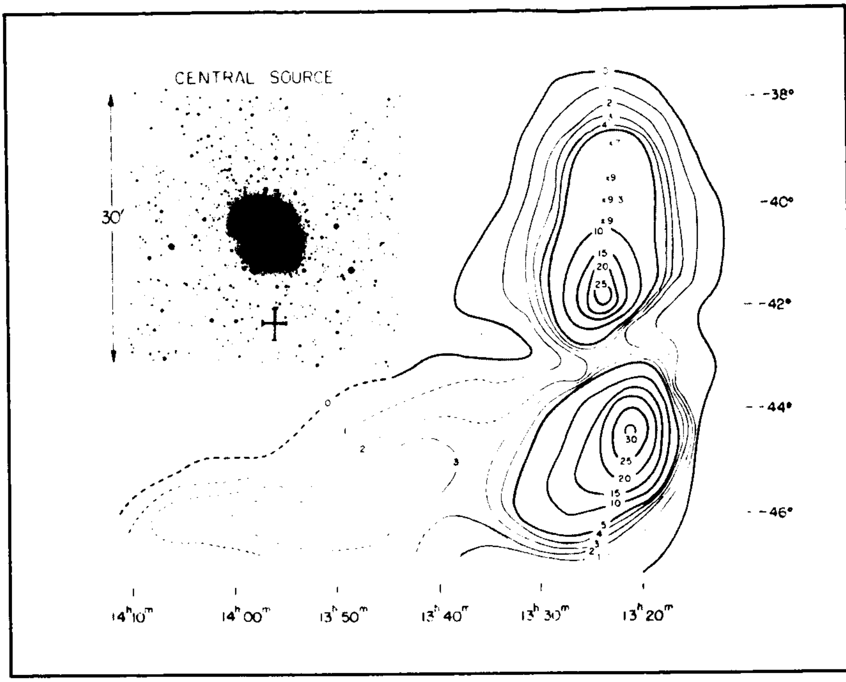


Figure 6—The extended source and the central source (inset) in Centaurus A. (Adapted from papers by Bolton and Clark and by Maltby.)

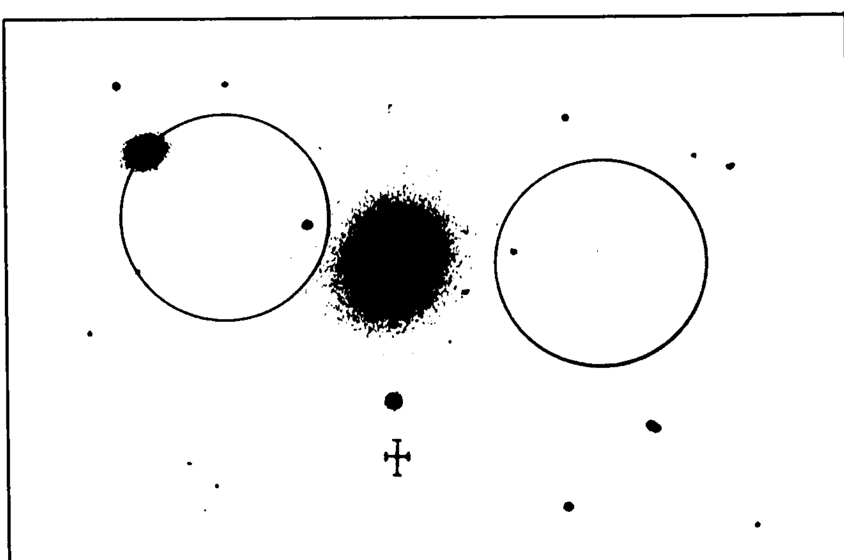


Figure 7—3C 270. The central galaxy is NGC 4261.

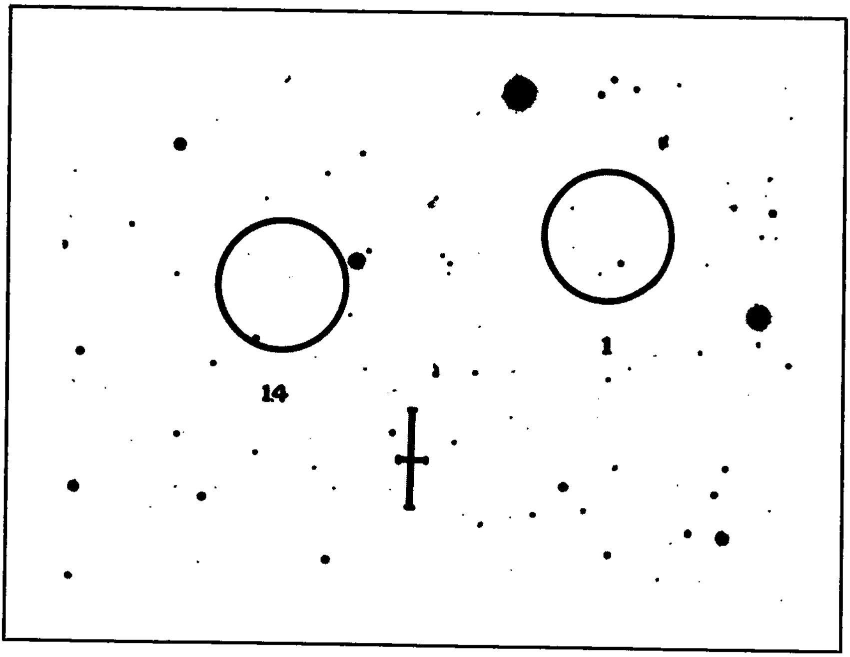


Figure 8—Hercules A.

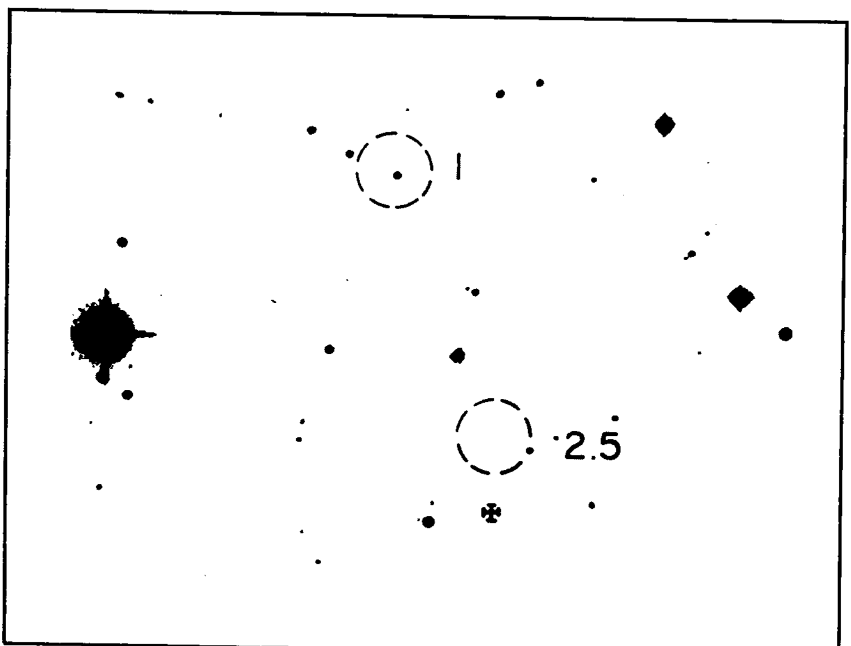


Figure 9—3C 33. The components of the radio source are much smaller than shown here.

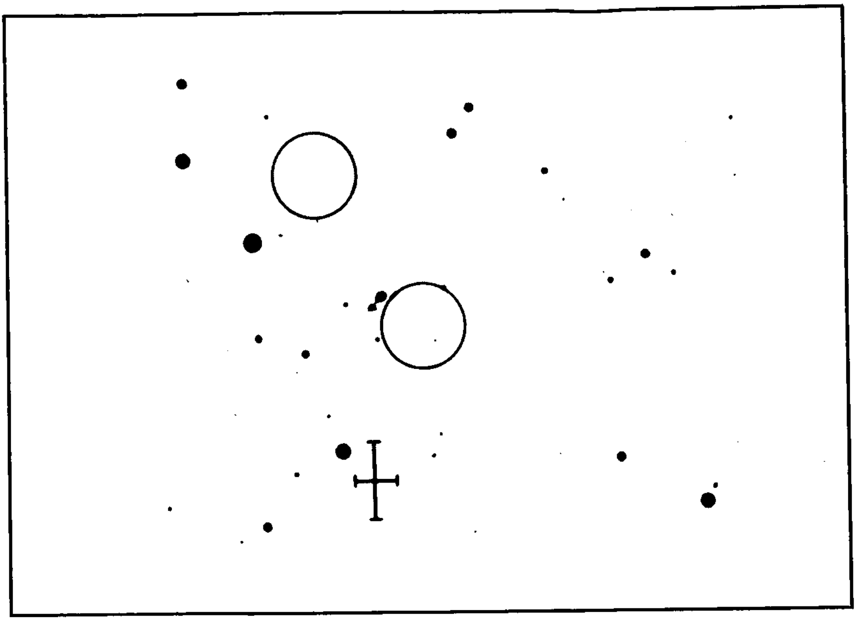


Figure 10—3C 219.

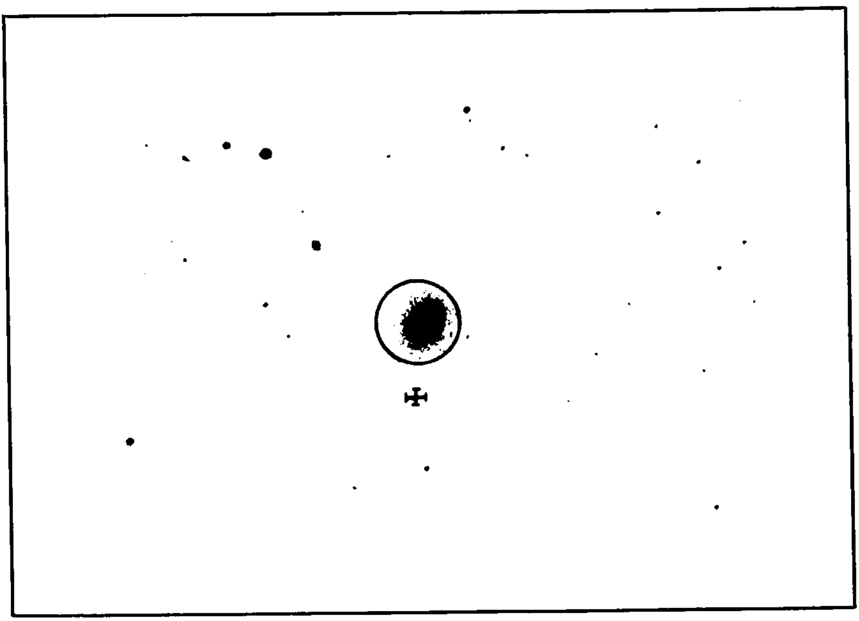


Figure 11—3C 78. The central galaxy is NGC 1218.

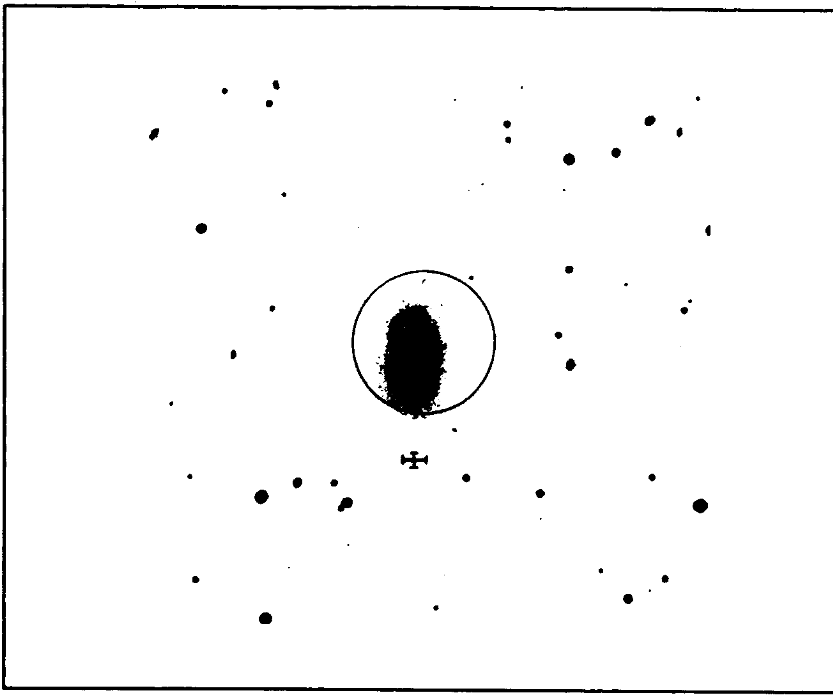


Figure 12—3C 278. The galaxies are NGC 4782 and NGC 4783.

complex structure. This conclusion is perhaps even better shown by Figure 13. The Jodrell Bank survey, carried out to much longer baselines, showed on a statistical basis that this predominance of complex structure continues down at least to angular diameters of 10″.

The distribution of intensity ratios for the components of double sources is given in Figure 14. Clearly this data is not complete for the high ratios, since in such cases one may fail to detect the fainter component. The first three columns, however. are probably complete, and they definitely suggest that there is a tendency for the components of a double source to have equal intensities.

The ratio of the inter-component spacing to the component diameter in a double source varies from roughly 2 to more than 10, with typical values of 3 or 4. This would seem to rule out a model based on a distribution of isotropically radiating toruses, since the expected ratio in that case would be about 1.5 to 2 depending on the thickness of a typical torus.

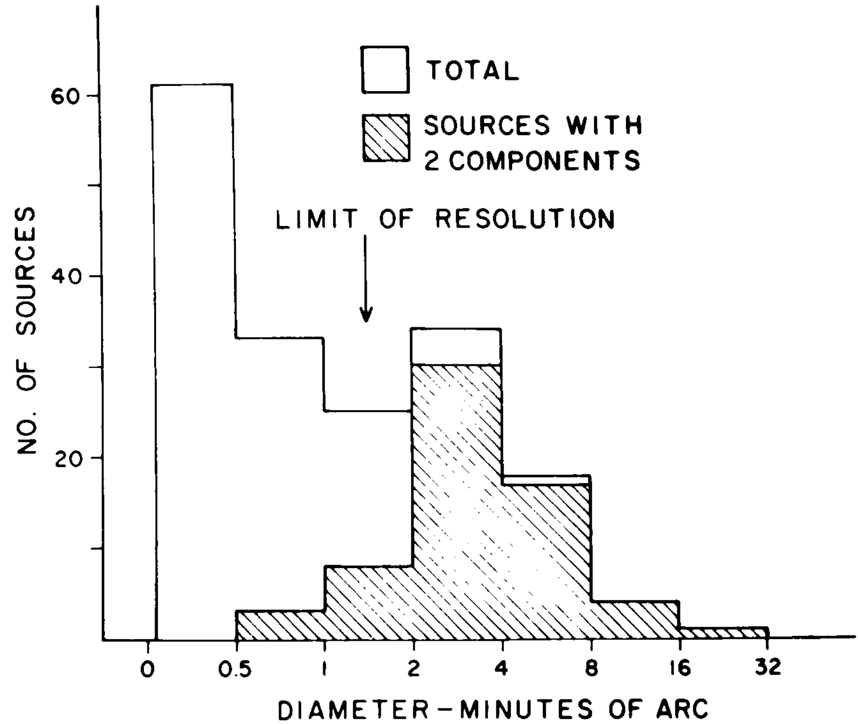


Figure 13—Histogram showing the predominance of complex sources among those resolved in the CalTech survey.

Comparison of the CalTech and Nancay decimetric data with the meter wave observations made at Jodrell Bank shows that for most sources of classes E and U, the brightness distribution is roughly independent of wavelength. In particular, the Manchester data taken with a 2200λ spacing at 1.7 m usually fit very well on the visibility curves of those sources which were observed at Nancay at 21 cm. As mentioned above, however, there is a variation in the appearance of the core-and-halo sources at different wavelengths, due to the steeper spectra of the halos.

The observed brightness temperatures for radio galaxies range from about 10° in the extended component of Centaurus A up to 7×10^6 °K for both Cygnus A and 3C 295. The typical value for extragalactic sources seems to be a few times 10^4 °K. Of course, there is the possibility that small diameter hot spots occur, with temperatures up to 10^6 °K or higher.

Linear Sizes

The diameters of the components of double sources range from less than 10 Kpc to over 100 Kpc, and the spacings between components range up to 300 Kpc. One halo source has a diameter as great as 250 Kpc. The simple sources, like the components of the doubles, have typical diameters of 30 Kpc.

Figure 15 is a comparison of three strong double sources, drawn to the same linear scale. 3C 295 was resolved with an antenna spacing of 62,000λ at Jodrell Bank, and found to be a double source whose components are separated by about 20 Kpc, that is, less than the diameter of the associated galaxy. In Cygnus A and Hercules A, the separations (projected on the plane of the sky) are about 80 and 200 Kpc, respectively. One is certainly tempted to think of these three sources as representing stages in an evolutionary sequence.

SUMMARY

To summarize briefly, we find that galactic nonthermal sources have more-or-less circular shapes; often they appear to have a shell-like structure, with a diameter of ~50 pc. The smaller SN remnants have diameters of a few parsecs and brightness temperatures of up to 10^5 °K. Extragalactic sources have brightness temperatures of up to at least 7×10^6 °K, but typical values

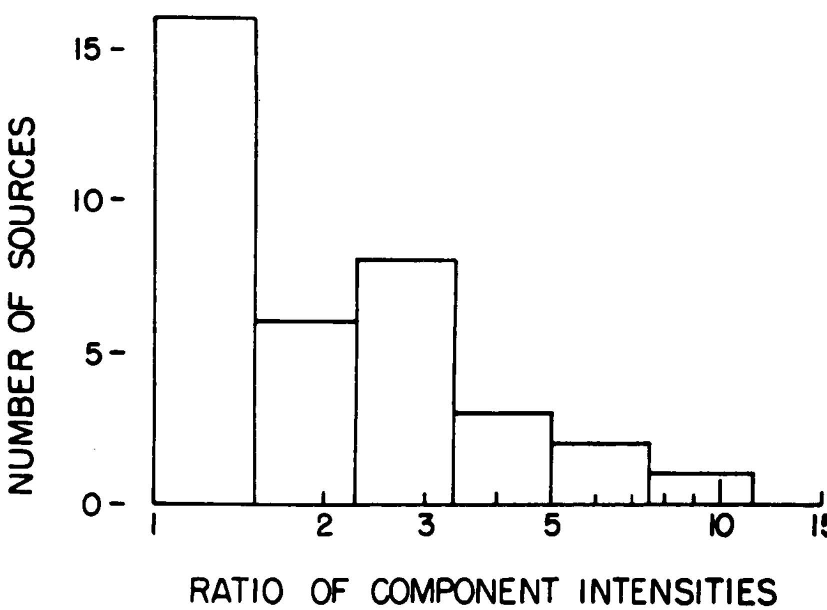


Figure 14—Histogram of the number of sources having a given ratio of component intensities. (From the CalTech survey.)

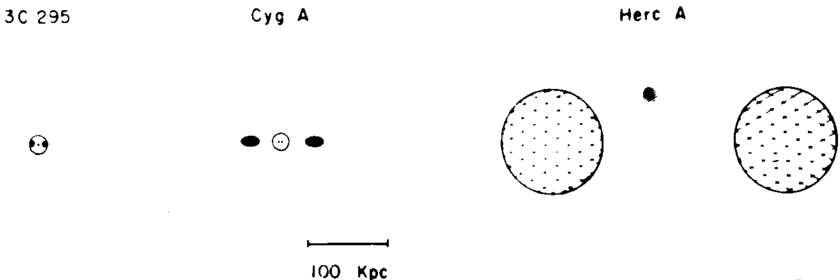


Figure 15—Comparison of three sources. 3C 295, Cygnus A and Hercules A are drawn to similar scale.

are a few times 10^4 °K. The predominant type of radio structure in extragalactic sources is that with two components, symmetrically disposed about the parent galaxy at distances of up to 150 Kpc. The components of these double sources have rather similar spectral characteristics, so that the appearance does not change greatly with wavelength. The components of core-and-halo sources *do* have different spectral behavior, however.

The linear sizes of the extragalactic sources are quite impressive, ranging up towards a megaparsec in several cases. The fact that these sources occupy such huge volumes poses a number of interesting physical problems.

SELECTED BIBLIOGRAPHY

(Since this report was not originally intended for publication, no attempt was made to collect a full set of references or even to give proper credit to those whose work has been reviewed. The following list of papers, while far from complete, should give the interested reader an introduction to the literature on source brightness distributions. It includes a few papers published since December, 1962.)

Techniques

Bracewell, R. N. (1958), Proc. I.R.E. *46*, 97.—interferometry
Moffet, A. T. (1962), Ap.J. Suppl. *7*, 93.—interferometry
Scheuer, P. A. G. (1962), Aust. J. Phys. *15*, 333.—occultations

Supernova Remnants

Harris, D. E. (1962), Ap.J. *135*, 661.—larger remnants
Woltjer, L. (1958), B.A.N. *14*, 39.—Crab Nebula
(Also Lequeux, and Moffet and Maltby—see Table I.)

Normal Galaxies

Brown, R. H. and C. Hazard (1959), M.N.R.A.S. *119,* 297.
——— (1961), M.N.R.A.S. *122,* 479.
——— (1961), M.N.R.A.S. *123,* 279.
Mathewson, D. S. and J. M. Rome (1963), Aust. J. Phys. *16,* 360.

Radio Galaxies

Allen, L. R., R. H. Brown and H. P. Palmer (1962), M.N.R.A.S. *125,* 57.
Bolton, J. G. and B. G. Clark (1960), P.A.S.P. *72,* 29.—Centaurus A
Hazard, C., M. B. Mackey and A. J. Shimmins (1963), Nature *197,* 1037.—occultation
Maltby, P., T. A. Matthews and A. T. Moffet (1963), Ap. J. *137,* 153.
Rowson, B. (1963), M.N.R.A.S. *125,* 177.—high resolution
Wade, C. M. (1961), Publs. Nat. Radio Astron. Obs. *1,* 99.
(See also the three surveys referred to in Table I.)

DISCUSSION

Roberts: In regard to the occultation results of Hazard and Mackey, mentioned by Dr. Moffet, here are some examples of the observations of 3C 273, made with the 210′ telescope at Parkes.

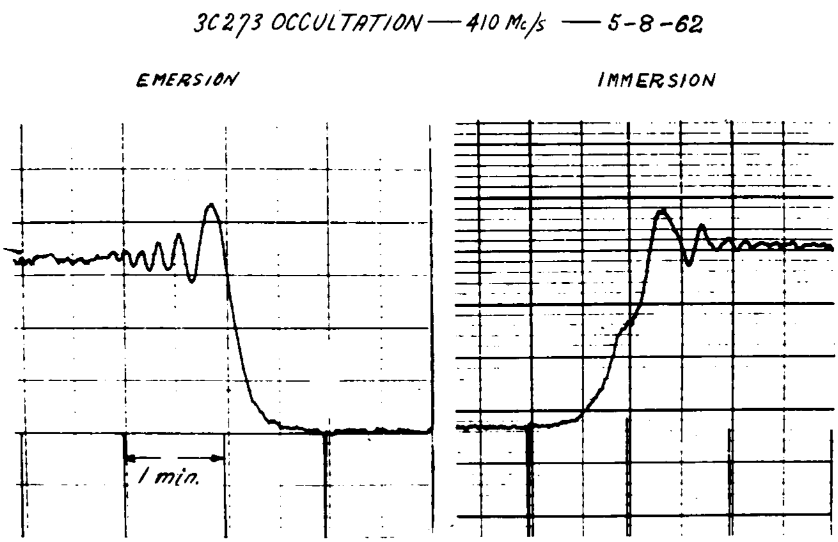


Figure 1.

Figure 1 is the record of observations made at 410 Mc/s, with the antenna tracking the source. Time increases from right to left. We note that there is a gap of just over an hour during which the source is occulted and that the source is oriented so that its double structure is evident only at immersion. The diffraction pattern indicates that 3C 273 is an extremely small source.

Figure 2 shows the record of another occultation, observed at 406 and 1440 Mc/s, at immersion only. A considerable difference in the spectra or polarizations (but presumably the former) of the two components clearly exists.

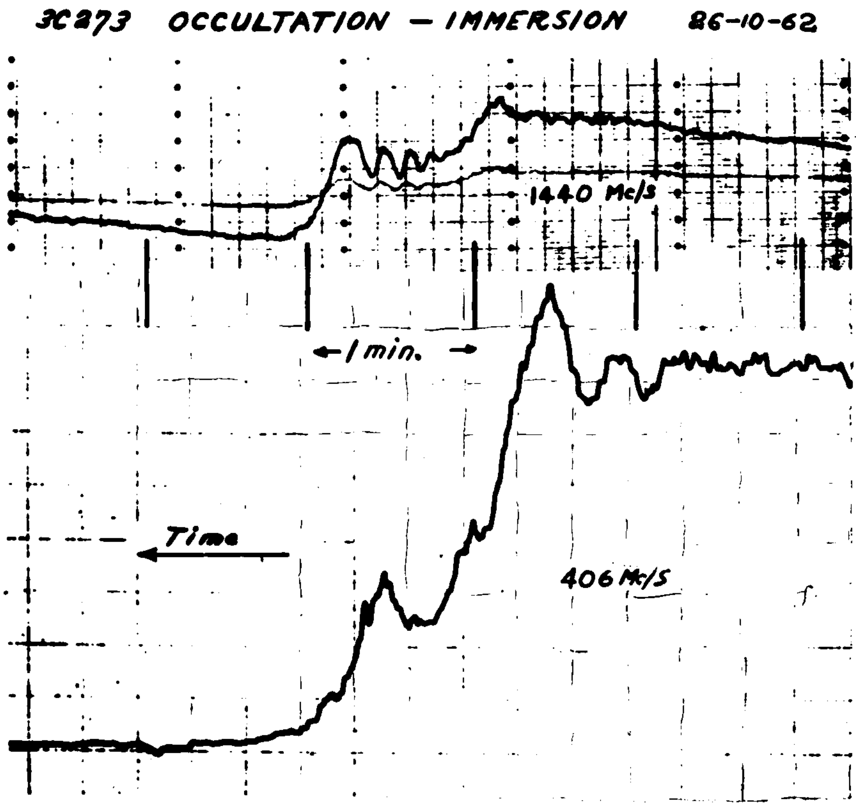


Figure 2.

Linear Polarization Effects in Radio Sources

J. A. Roberts
COMMONWEALTH SCIENTIFIC
AND INDUSTRIAL RESEARCH ORGANIZATION
DIVISION OF RADIOPHYSICS, SYDNEY

INTRODUCTION

Of the current observing programs on the C.S.I.R.O. 210′ radio telescope at Parkes, the program to measure the polarization of radio sources has produced the most unexpected results. Three polarization studies were scheduled for the first observing quarter —observations of Jupiter, a search for linear polarization in the emission of discrete sources, and observations to confirm the Dutch findings of polarization in galactic radiation. Of these three, the studies of discrete sources have proved so fruitful that they have taken precedence over the other programs.

The first important result was the detection of linear polarization at a wavelength of 10 cm in one of the central sources of Centaurus A by Bracewell, Cooper and Cousins. (*1*) Then Cooper and Price (*2*) showed that at three different points in Centaurus A the position angle of the electric vector varied as λ^2 over a considerable range of wavelength, and they therefore suggested that Faraday rotation had been observed.

Working at a wavelength of 21 cm Gardner and Whiteoak (*3*) found linear polarization in seven of the first nine extragalactic sources which they examined. Among their results was the discovery of 38% polarization in part of Centaurus A. They have now completed a study of eighteen polarized sources measured at two or more wavelengths and have produced the first attempt at a map of the variation of the Faraday rotation over the sky. (*4*)

While these observations have been in progress we have heard that polarization studies were being pursued also at N.R.L. and at CalTech. I think that this meeting will provide an excellent opportunity for us to exchange information and to assess the present position. I would certainly like to thank N.A.S.A. for making my attendance here possible.

OBSERVING TECHNIQUE AND INSTRUMENTAL EFFECTS

All the observations at Parkes were made with the 210′ telescope equipped with linearly polarized feeds (Fig. 1). The search for polarization was made at wavelengths of 10, 21, and 74 cm, and sources found to be polarized were further examined at other wavelengths between 10 and 30 cm. The 21 cm receiver uses a parametric amplifier (*5*) with a noise temperature of about 100°K. The original 10 cm receiver was an obsolete model with a receiver noise temperature of some 1500°K. Since the antenna has been found to perform well at this wavelength, an 11 cm parametric amplifier has been constructed and will soon be in operation.

The feeds employed have been either double dipoles with a reflector, or rectangular horns, depending on the wavelength. Their dimensions were chosen so as to give essentially circular beams. The feeds are mounted on circular plates 20 inches in diameter which fit into a feed rotator. The phase centre of the feed is located at the centre of the plate, ensuring that it can be rotated without changing the pointing. This also allows feeds to be changed to observe at different wavelengths without altering either the pointing or the focus. The rotator can be driven at either 1.5 or 3 degrees per second, and the feed angle is indicated by a selsyn repeater in the control room.

Three observing methods have been used for source polarization measurements:

(i) Rotating the feed with the antenna directed first at the source and then at nearby points in the sky,

(ii) Scanning through the source at a number of fixed feed angles, usually six angles spaced at intervals of 30°, and

(iii) Tracking first the source and then some nearby points in the sky at several fixed feed angles.

The main instrumental effect is a modulation of the base level as the feed is rotated. This is demonstrated by rotating the feed while observing unpolarized sources of various intensities and finding that the pattern is essentially the same as that on nearby parts of the sky. Any true instrumental polarization, that is a variation of the output which is proportional to the flux of the source, is less than 0.5% at wavelengths greater than 20 cm, and ~1% at a wavelength of 10 cm. The number of unpolarized sources so far observed is not sufficient to provide a complete understanding of these instrumental effects, so that the results presented here have been corrected only for the modulation of the base level. Fortunately the other instrumental effects tend to be averaged out by making observations with the alt-az mounted dish at a number of different hour angles. This is an important advantage of the alt-az mount for polarization work.

The modulation of the base level depends somewhat on both the zenith angle and the type of feed used. Gardner believes the effect is due to radiation scattered from asymmetrical parts of the antenna structure, or to ground radiation picked up in the side lobes.

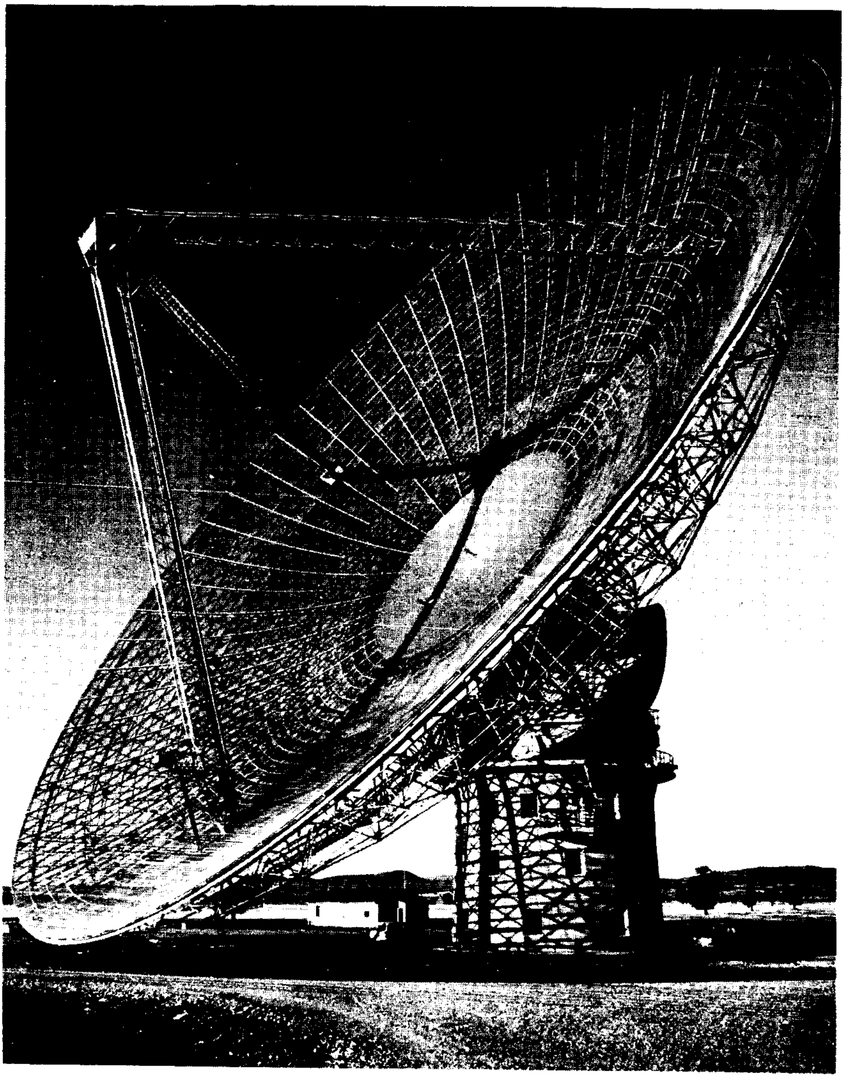


Figure 1—The 210′ radio telescope of the Australian National Radio Astronomy Observatory at Parkes, NSW, Australia.

The effect of correcting for this instrumental effect is illustrated by the records shown in Fig. 2. Here the unbroken curves show a rotation on-source, the dashed curves a rotation off-source, and the dotted curves below show the difference. The examples shown are Fornax A, a relatively strong source with a pronounced degree of polarization, and 3C 161, a weaker source with a lower polarization temperature. Notice that even for the weaker source there is a relatively well-defined sine wave when the difference is taken. This observation of 3C 161 was taken with the multiple wavelength feed, so that the base level modulation is relatively large.

SUMMARY OF RESULTS

Figures 3 and 4 present a summary of the results of Gardner and Whiteoak for all the sources which they have observed at three or more wavelengths. For each source the left-hand diagram in these figures shows the position angle of the polarized component and the right-hand diagram shows the degree of polarization, both as functions of the square of the wavelength.

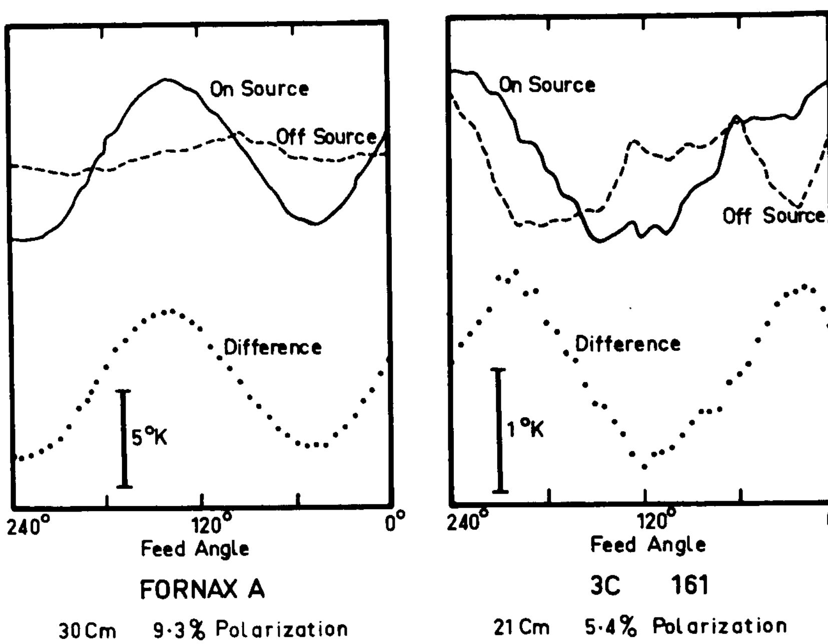


Figure 2—Records made by rotating a linearly polarized feed with the antenna directed at the source (full curve) and at a nearby point in the sky (broken curve). The dotted curve below shows the difference between the curves. (Observations by Gardner and Whiteoak.)

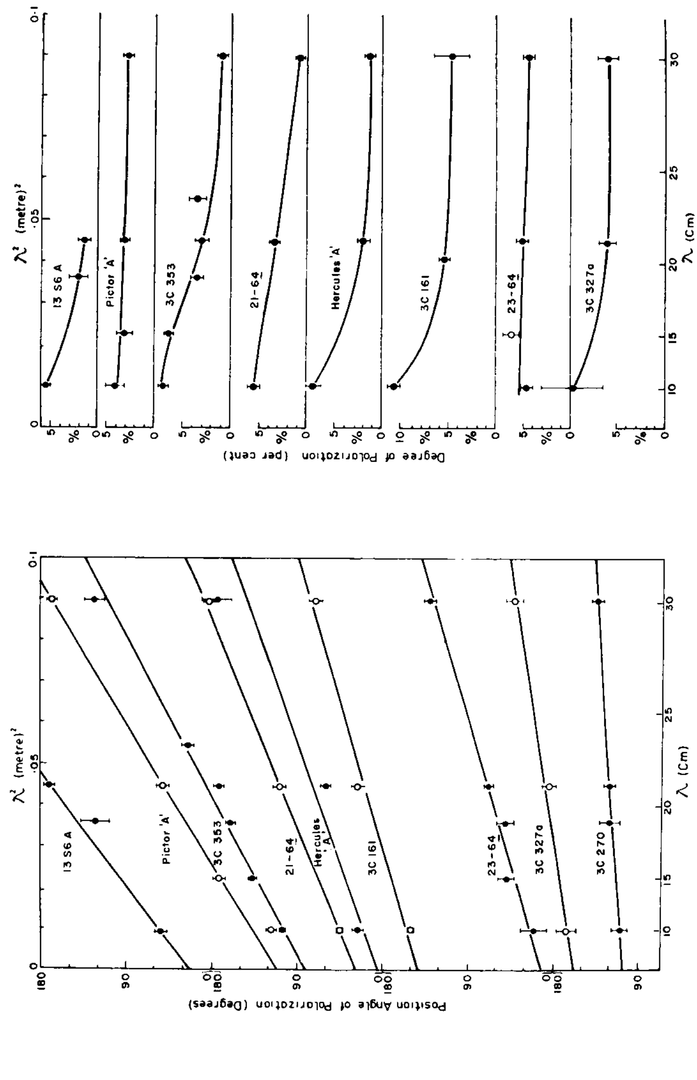


Figure 3—*Plots of the polarization position angle (at left) and of the percentage linear polarization (at right) as a function of the square of the wavelength for a number of sources. This figure shows the sources with positive rotation measures arranged in order of decreasing rotation measure. (Data from Gardner and Whiteoak.)* Note. *See the revised conclusion concerning 180° ambiguities for the source 3C 161 in the note by Gardner which follows this paper.*

The degree of polarization is defined as the ratio of the polarized flux to the total flux. If a rotating linearly polarized feed is used the

$$\text{degree of linear polarization} = \frac{S_{\max} - S_{\min}}{S_{\max} + S_{\min}},$$

S being the flux density. The position angle refers to the electric vector and is measured East from North. Notice that there is an ambiguity of $n \times 180°$ in the position angle. In Figs. 3 and 4 Gardner and Whiteoak have resolved this ambiguity by choosing the lowest values which give a reasonable approximation to a straight line.

The slope of the position angle versus λ^2 line is a fundamental property of the radio source as observed on the Earth. Pawsey suggested that this quantity should be called the *rotation measure* by analogy with the term *emission measure*. A positive rotation

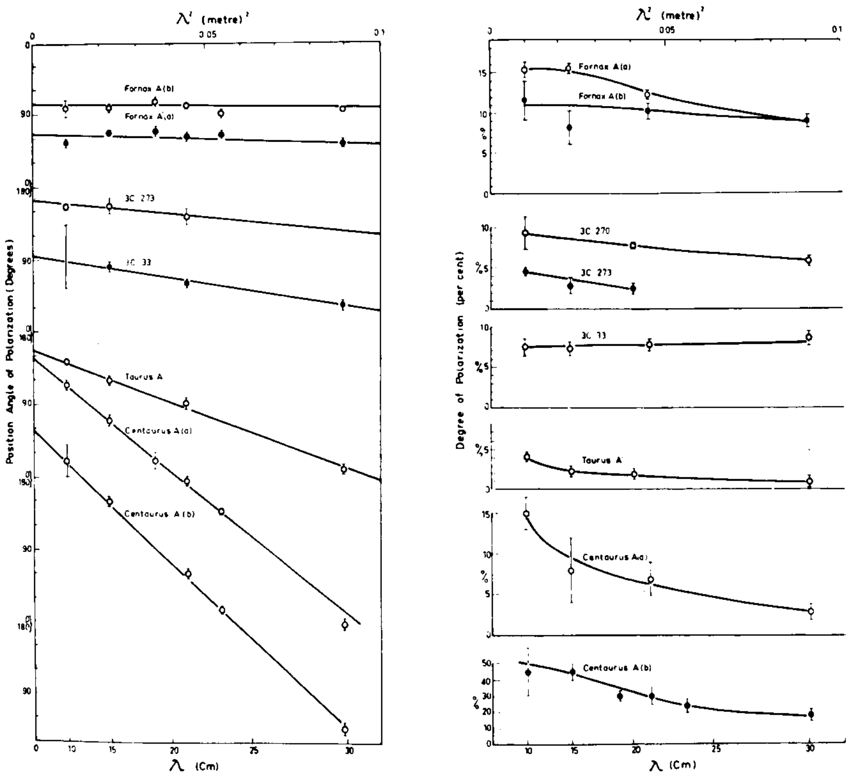


Figure 4—Same as Fig. 3, for sources with negative rotation measures.

measure indicates an increase of the position angle with wavelength.

The left hand diagrams of Figs. 3 and 4 show that the observed position angles vary approximately linearly with λ^2. This is what one expects for Faraday rotation in an ionized gas at frequencies well above the critical frequencies. In this case the

$$\text{rotation measure} = 8.1 \times 10^5 \int n_e B_{\parallel} \, ds \text{ rad } m^{-2}.$$

Here the component of the magnetic field parallel to the line of sight, $B_{\parallel}$, is expressed in gauss, the electron density n_e in cm^{-3}, and the distance s in parsecs. The constant multiplier is chosen so that the units of rotation measure are radians per square meter, as recommended by Gardner and Whiteoak. A *positive* rotation measure corresponds to $B_{\parallel}$ directed *towards* the Earth. It is seen from Figs. 3 and 4 that both senses of rotation are observed. There are departures from the λ^2 law in some cases (see *e.g.* 3C 353 in Fig. 3), and these may provide important information about the rotating medium.

THE ORIGIN OF THE ROTATION AND DEPOLARIZATION

We must first consider the origin of the observed rotation. Where is it produced? There is still considerable room for doubt in this matter, but we will present data which suggest that the rotation occurs within our Galaxy. Figure 5 shows the distribution of the observed sources in galactic coordinates, with the magnitude and sense of the rotation measure indicated by the size and nature of the spot. The dotted line indicates the area which is not accessible to observation with the 210′ telescope. Notice that some sources which are fairly close together on the sky have opposite senses of rotation, and that there is a tendency for the larger values of the rotation measure to occur at lower galactic latitudes. The upper graph in Fig. 6 is a histogram of the frequency of sources as a function of galactic latitude, for different values of the rotation measure. The statistical sample is small, but the data are certainly suggestive of a decrease of rotation measure with galactic latitude. We see (Fig. 5), that in the present sample at least, there is a predominance of positive rotation measures.

From the right hand graphs of Figs. 3 and 4 it is clear that for most sources the degree of polarization decreases with increasing wavelength. This is an effect which has been known for the Crab Nebula for some time. Not all sources show the effect; *e.g.* for

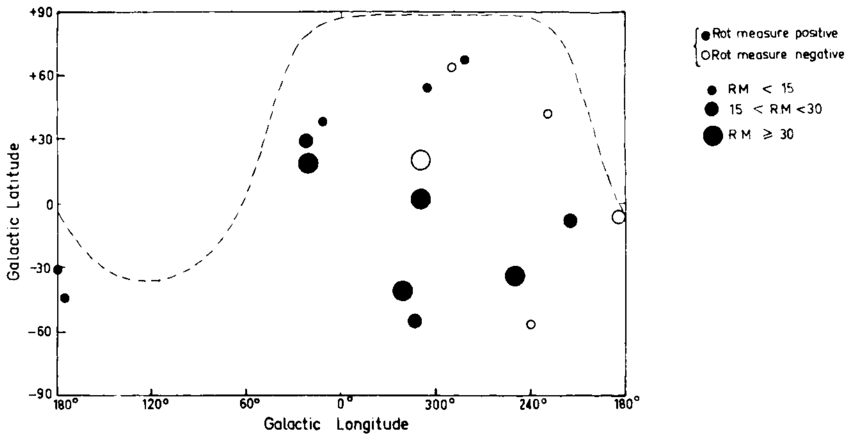


Figure 5—Each point represents a polarized source in galactic coordinates. The nature of the spot indicates the magnitude and sign of the rotation measure as indicated. The dashed line shows the limits of observation with the 210′ telescope. (Gardner and Whiteoak data.)

3C 33 (Fig. 4) the degree of polarization is relatively independent of wavelength. Also, Gardner and Whiteoak have found a few sources, so far observed at only two wavelengths, in which there is a higher degree of polarization at the longer wavelength.

Synchrotron emission has a very wide natural bandwidth: a single electron has a bandwidth of a factor of four between half power points. Thus, if this radiation is generated by the synchrotron process, one would not expect the intrinsic polarization of the source to be a rapid function of the wavelength. The observations thus suggest that for most sources the radiation is being depolarized after generation, at least at the longer wavelengths. If the radiation from different parts of a discrete source is rotated through different angles, then depolarization due to the differential Faraday rotation will occur. Thus it is natural to ask whether the depolarization found is consistent with the observed Faraday rotation. Can inhomogeneities in the medium which produces the rotation be responsible for the depolarization?

The lower histogram of Fig. 6 shows a test of the dependence of the depolarization on galactic latitude. We took, as a rough measure of the depolarization, the ratio of the degree of polarization at a wavelength of 10 cm to that at 20 cm, or the corresponding ratio for wavelengths of 20 and 30 cm, or when there were data for all three wavelengths, the average of these two ratios. A histogram was then constructed in the same way as was done for the rotation measure. From Fig. 6 it is seen that the histogram for the depolarization is similar to that for the rotation measure. The sources which depolarize most rapidly tend to occur at low galactic latitudes, supporting the idea that the depolariza-

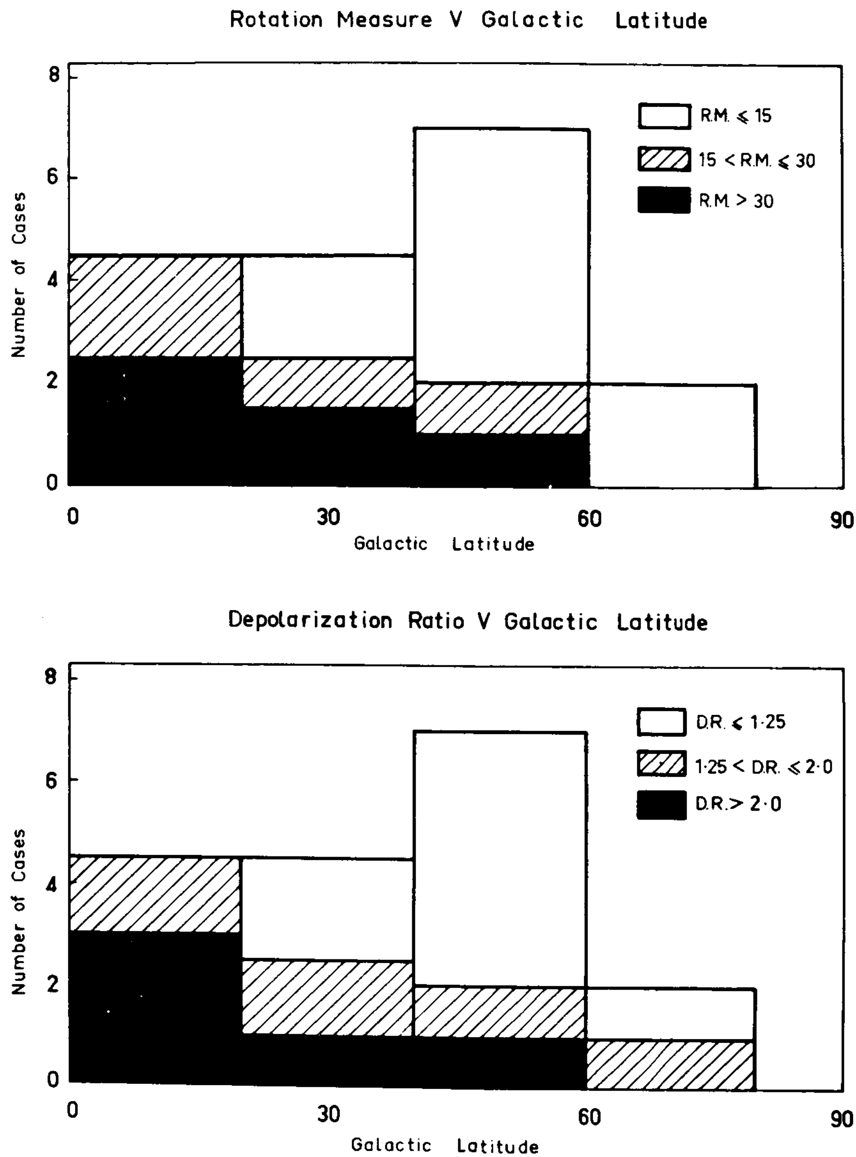


Figure 6—Histograms showing the distribution of the polarized sources observed by Gardner and Whiteoak against galactic latitude. The shading in the upper diagram indicates the magnitude of the rotation measure, and that in the lower diagram the magnitude of the depolarization ratio.

tion occurs by differential Faraday rotation in a medium within our Galaxy.

If the depolarization is caused by differential rotation in a medium between the observer and the source then the transverse angular scale of the inhomogeneities must be small compared with that of the source. Furthermore when there is differential Faraday rotation, whether it occurs in front of the source or within the source, the λ^2 law for the position angle does not necessarily hold. Komesaroff in Sydney, as well as others (*6*), has shown that there is a Fourier transform relationship between the observed polarization and the ratio of the emissivity to the rotary power of the emission. Although the theory is still in a preliminary state, a few models computed by Komesaroff suggest that when differential Faraday rotation is present the λ^2 rotation law will hold up to the wavelengths at which substantial depolarization is observed. Beyond this range there will be drastic departures from this simple law.

Let us consider the possibility that the observed Faraday rotation originates in our Galaxy. Figure 6 shows that at a galactic latitude of 20° we must account for a rotation measure of about 20, which means that

$$\int n_e B_{\parallel} ds \approx 2 \times 10^{-5}.$$

With very "reasonable" values the integral can attain this value. For example if

$$\int ds = 5 \text{ kiloparsecs}$$
$$n_e = 10^{-2} \text{ cm}^{-3}$$
$$B_{\parallel} = 5 \times 10^{-6} \text{ gauss}$$

then the integral is too large by a factor of ten and we can allow quite a few reversals of the field along the line of sight. Alternatively, one might imagine an isolated cloud that happens to be in front of the source. Then we can take

$$\int ds = 10 \text{ parsecs}$$
$$n_e = 1 \text{ cm}^{-3}$$
$$B_{\parallel} = 5 \times 10^{-6} \text{ gauss}$$

and the rotation measure will be sufficient. The emission measure of such a cloud will be only 10, and it would not be detectable optically.

If the depolarization occurs within our Galaxy we can state a requirement for the scale of the inhomogeneities. Several of the depolarized sources have diameters of a few minutes of arc. Since there must be differential effects across the diameter of the source, the scale of the inhomogeneities must be as small as tens of seconds of arc. However the changes over such distances need not be by an order of magnitude.

POLARIZATION AND SOURCE STRUCTURE

The distribution of polarization over a source and its relationship to the source structure provide information about the shape of the magnetic field in the source. Since for a synchrotron source the generated polarization should be relatively independent of the wavelength, extrapolation of the plot of polarization angle versus wavelength to zero wavelength should yield the polarization at emission. Gardner and Whiteoak term this the *intrinsic polarization.* It is this quantity which should be compared with the source structure.

Many of the polarized sources are double. There are ten such in the present list, and naturally one looks to see if there is any relation between the direction of separation of the pair and the direction of the intrinsic polarization. However the present data seem to be randomly distributed in this respect. The intrinsic polarizations tend to be quite low in most cases, perhaps 10 or 15%. The circumstance suggests that a given source may contain magnetic fields with many orientations, so that the net polarization is quite low. If this is true it is perhaps not surprising that there is no relationship between the direction of polarization and the structure of the source. However, further progress in this matter requires detailed observations of polarization as a function of position over the source.

There are two polarized sources which can be readily resolved with the 210′ radio telescope, Centaurus A and Fornax A. Figure 7 shows a map of Centaurus A which has been made by Cooper and Price at a wavelength of 21 cm. The contours show total intensity, that is the sum of the intensity observed in two orthogonal planes of polarization. The small lines show the position angle, and their lengths indicate the degree of polarization. A dot indicates that observations have been made, but that the polarization was very low. Notice that along the ridge in the northern extended source the polarization reaches 40%.

The position angles shown in this figure are the observed directions at 21 cm and have not yet been corrected for Faraday rotation. So far the Faraday rotation has been measured at three points on this source. At each point the rotation was similar and amounted to between 150° and 165° for the interval between 21 cm and zero wavelength. Thus the map may in fact be approximately

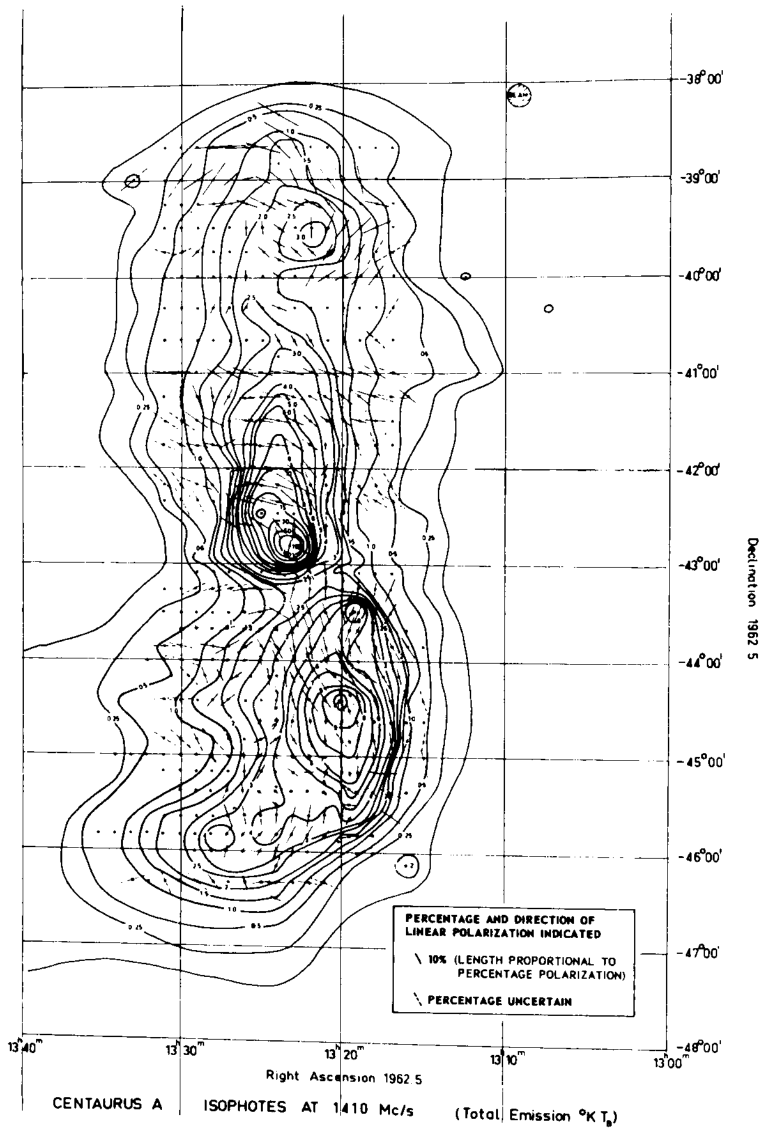


Figure 7—Map of Centaurus A made by Cooper and Price at a wavelength of 20 cm. The contours show the total intensity (two planes of polarization) and the small lines show the direction and degree of linear polarization. These are the observed values and have not been corrected for Faraday rotation.

a map of the intrinsic polarization. If so it would seem that the magnetic field, which will be perpendicular to the intrinsic polarization, must have a complex form. We await with interest Cooper and Price's projected study of this source with the 10 cm parametric receiver, which should allow them to map the intrinsic polarization.

REFERENCES

(*1*) Bracewell, R. N., B. F. C. Cooper and T. E. Cousins (1962), Nature *195*, 1289.

(*2*) Cooper, B. F. C. and R. M. Price (1962), Nature *195*, 1084.

(*3*) Gardner, F. F. and J. B. Whiteoak (1962), Phys. Rev. Letters *9*, 197.

(*4*) ——————————— (1963), Nature *197*, 1162.

(*5*) Gardner, F. F. and D. K. Milne (1963), Proc. I.R.E. (Aust.) *24*, 127.

(*6*) See *e.g.* Burn, B. J. and D. W. Sciama, this volume.

DISCUSSION

Greenstein: Hasn't it been shown that the mean polarization observable for a dipole field is not very large? If one takes a simple dipole field and admits both a distribution of pitch angles and also the fact that the field lines are turned, then the mean polarization is a function of the orientation of the observer's line of sight with respect to the dipole orientation, and for probable angles, it is in fact not much larger than 10 per cent. Thus the intrinsic polarization in the simplest of all cases will not in fact be expected to be very large, and then if one has a mixture of several randomly oriented dipoles, one goes down by the square of n, approximately, from that value. It would seem then, that high intrinsic polarization would in fact be very difficult to understand.

Roberts: The degree of polarization for the dipole case depends on the pitch angle distribution. Chang calculated a case for Jupiter in which he managed to get about 30% polarization. Further, on this model we would expect sometimes to observe rings, which seems to conflict with Moffet's information about source shapes.

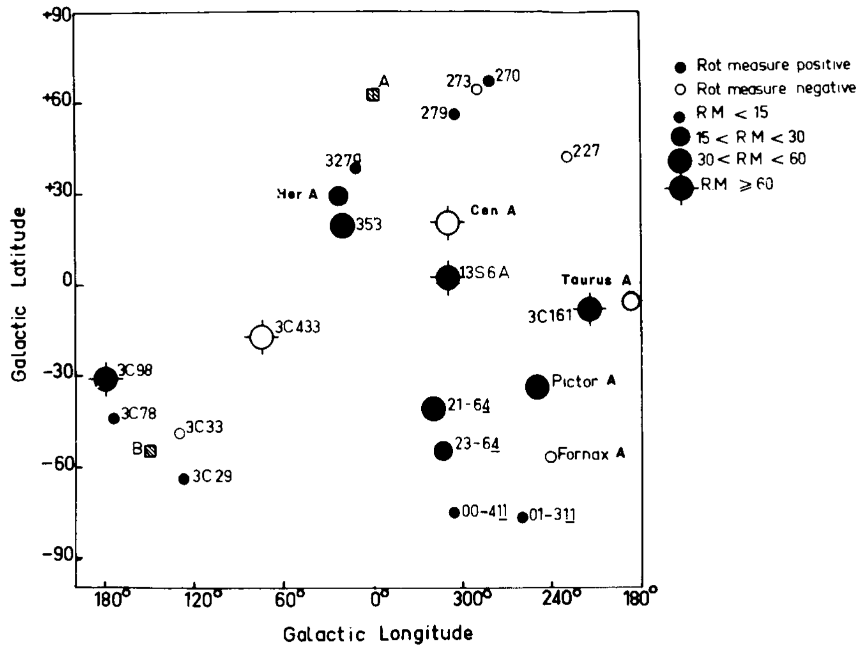


Figure 1.

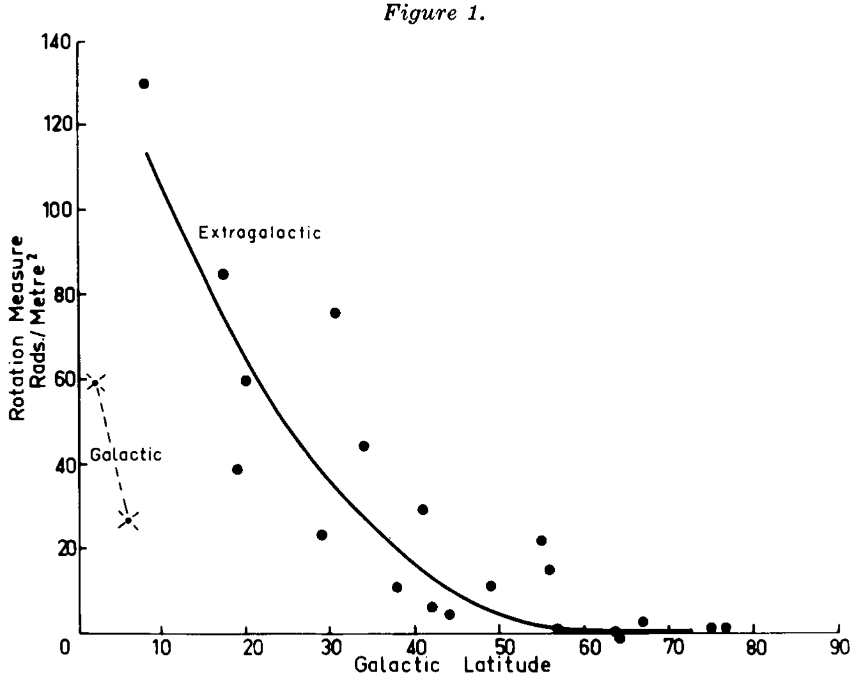


Figure 2.

ADDED BY F. F. GARDNER:

Figure 1 (page 50) shows a more recent plot of Faraday rotation against galactic coordinates. In addition to a number of new sources there have been two changes, 3C 98 and 3C 161. The former was previously measured at 2 wavelengths only. A third wavelength removed the ambiguity and showed that the Faraday rotation was large and positive. With 3C 161 the sign is the same but the rotation measure is considerably larger, 130 radians/metre^2, the largest observed up to the present. With these amendments, plus the new sources plotted in Fig. 1, there is a clear dependence of the absolute value of Faraday rotation on galactic latitude, as shown in the plot of Fig. 2.

For the double sources there is a tendency for the intrinsic polarization direction to be either parallel or perpendicular to the direction of separation of the plane. From a sample of 12, the difference between the two directions lies between 0 and 30° in seven cases, and between 60° and 90° in five cases. There are none between 30° and 60°.

Polarization Studies of Discrete Radio Sources

V. Radhakrishnan
OWENS VALLEY RADIO OBSERVATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

The observations discussed in this paper constitute the work of a group of CalTech radio astronomers in which the author has played only a small part. Our first careful attempts at the measurement of polarization in discrete radio sources were made in the summer of 1961, when we still held the mistaken notion that the degree of polarization which might exist for a typical radio source at decimeter wavelengths was of the order of 1% or less. For that reason, we concentrated on improving our observational techniques and reducing instrumental effects.

Six sources were studied at that time: two emission nebulae (Orion and Omega), two external galaxies (Cygnus A and Virgo A) and two supernova remnants (Cassiopeia A and the Crab). Of these sources, the Crab Nebula was the only one then known to be polarized at higher frequencies. A null method of measurement was used in which the polarized flux component of the source was balanced against the unpolarized component. In this way it was possible to avoid an instrumental effect proportional to the intensity of the source. The results obtained were a linear polarization of 1.5% for the Crab Nebula and an upper limit of about 0.3% for the other five sources.

When the plane of polarization of the Crab Nebula was plotted against λ^2, using the optical data, the N.R.L. 3 and 10 cm results, and our 21 cm measurement, it was apparent that a straight line would not fit all the points. In fact, the best possible straight line through all the radio frequency points missed the optical value by about 10° in position angle. In other words, it appeared as though the average plane of polarization at optical frequencies was slightly inclined to the average radio frequency plane of polarization. Similar difficulty was experienced in trying to fit a straight line through the values of fractional polarization plotted against λ^2. On such a plot the slope of the line was steeper at centimeter wavelengths than in the decimeter region. It seems strange that the Crab Nebula should be polarized out to 21 cm and Cassiopeia A not at all even at 3 cm, as shown by the N.R.L. and Michigan measurements. If some remnants of supernovae are polarized and others not, one wonders whether there is a dependence on the age, position in the galaxy or the type of supernova.

Stimulated by the detection of polarization in two radio galaxies, Cygnus A and Centaurus A, by Mayer and others at N.R.L., the polarization program at CalTech was intensified this year and as a result a large number of sources have been observed for polarization at three frequencies. The results of measurements carried out in the period July to November, 1962, are listed in Table 1. Where data in the table are enclosed in parentheses we believe the results to be merely indicative of an upper limit to the degree of linear polarization. These data have been included mainly for comparison with the results of other observers who might have been more successful in detecting polarization in these sources.

Among the sources observed were Kepler's and Tycho's supernovae. By studying their radio spectra, Harris has classed these two together with the Crab while grouping Cassiopeia A with a number of other remnants. Kepler's SN showed no evidence of polarization greater than 1% at any of the three frequencies. Tycho's SN on the other hand appears definitely polarized at 10 cm, although not detectably so at 21 cm. (The value listed in the table, however, is not directly comparable to a measurement made at the same frequency with a single antenna, as our interferometer measurement was made at a baseline where the source was considerably resolved.)

The apparent polarization measured with an interferometer on a resolved source depends on the distribution of the polarization over the surface of the source. Early in the program it was noticed that the polarization was not uniform over some of the sources, as evidenced by an apparent dependence of the measured percentage on the amount of resolution involved. In the case of the Crab Nebula, for instance, 3.7% polarization was measured at 10 cm when the source was negligibly resolved, but 6% was recorded when the visibility amplitude was 0.4. This observation is reconcilable with the idea that the source consists of a large unpolarized region with a small polarized region at its center. However, the optical data on the Crab Nebula lead one to suspect that one would detect fine structure in the distribution of polarized radio radiation over the source if it could be sufficiently resolved.

TABLE 1. SOURCES OBSERVED FOR POLARIZATION AT CALTECH

Source	21 cm %	21 cm P.A.(°)	18 cm %	18 cm P.A.(°)	10 cm %	10 cm P.A.(°)	Identification
3C 10*					2.7	45	Tycho's SN
20	(1.8 ± 1.0	126 ± 15)					
33	7.7 ± 0.7	62 ± 3	7.2 ± 0.6	72 ± 5	8. ± 1.3	88. ± 7	17^m galaxy
48	(0.7 ± 0.6	162 ± 25)			3.4 ± 1.	75 ± 10	†
66*	2.9 ± 0.5	83 ± 5					
78					2.3 ± 1.7	85 ± 14	
84	(0.8 ± 0.6	37 ± 21)	(1. ± 0.7	172 ± 20)	(1.5 ± 1.0	102 ± 6)	NGC 1275
98	4.6 ± 1.0	62 ± 6	5.8 ± 0.6	16 ± 5	7. ± 2.8	111 ± 11	16^m galaxy
111	2.2 ± 0.6	92 ± 9	2.1 ± 0.4	120 ± 8	3.3 ± 1.8	116 ± 14	
123	(0.5 ± 0.4	68 ± 24)			(0.4 ± 0.3	69 ± 15)	
CRAB N.	1.5 ± 0.1	89 ± 5	1.75 ± 0.25	95 ± 5			SN
3C 147	(0.2 ± 0.5	138 ± 57)			(0.9 ± 0.9	104 ± 18)	†
161	5.8 ± 0.5	29 ± 3	9. ± 0.7	122 ± 5	9.5 ± 1.2	168 ± 5	
196	(0.4 ± 0.5	155 ± 38)			(1.5 ± 1.0	90 ± 20)	†
227					3.9 ± 2.0	153 ± 16	
M 82					3.5 ± 1.3	35 ± 11	Galaxy
3C 273	2.1 ± 0.3	158 ± 3	2.4 ± 0.5	178 ± 7	3.4 ± 0.3	147 ± 4	†
286	9.3 ± 0.5	32 ± 2	8.7 ± 0.7	34 ± 5	9.0 ± 1.0	29 ± 4	†
295	(0.5 ± 0.5	160 ± 27)			(0.4 ± 2.0	72 ± 156)	$20^m.9$ galaxy
327	3.7 ± 1.6	7 ± 14					17^m galaxy
HER A	1.4 ± 0.4	59 ± 8	2.1 ± 0.4	52 ± 4			18^m galaxy
3C 353	2.9 ± 0.4	0 ± 4	3.8 ± 0.5	165 ± 6			16^m galaxy
358					(0.8 ± 0.9	117 ± 34)	Kepler's SN
380	1.4 ± 0.7	72 ± 14	1.6 ± 0.5	34 ± 9	(1.0 ± 0.8	21 ± 24)	
433	4.7 ± 0.6	150 ± 4	6.9 ± 0.9	26 ± 7	5.7 ± 1.0	122 ± 5)	17^m galaxy pair
452*	5.5 ± 0.9	23 ± 5					19^m galaxy
VENUS					(0.6 ± 1.1	111 ± 54)	Planet

* The measurements of these sources are not directly comparable with single antenna measurements at the same frequencies.

† Optically these objects present a stellar appearance. At the time of the conference they were thought to be galactic objects.

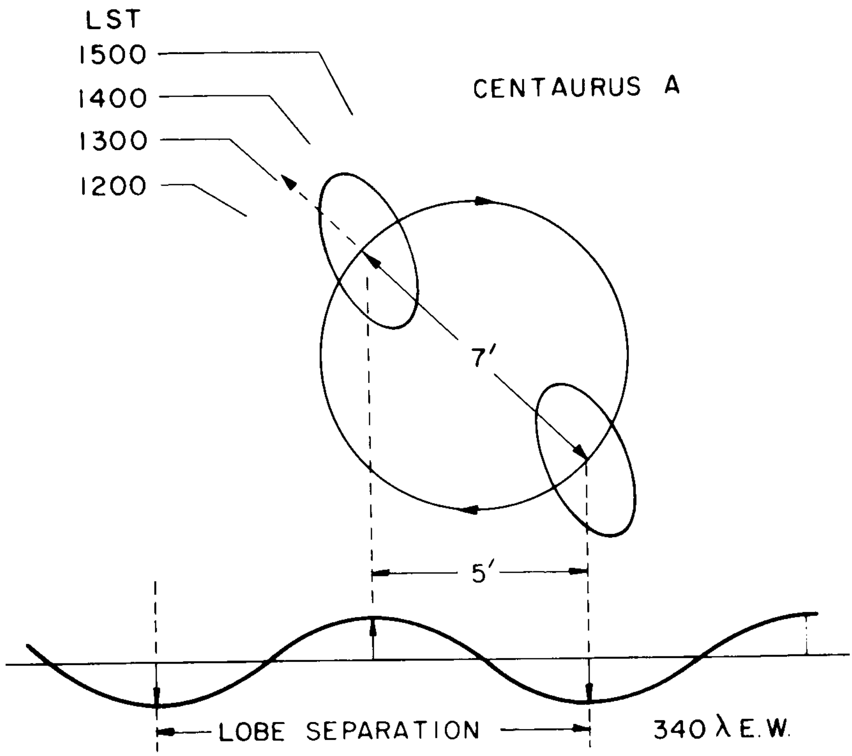


Figure 1.

The source 3C 353, on the other hand, showed an apparent decrease in the percentage polarization with increasing resolution. Other sources that were easily resolved at the spacings and wavelengths used were Centaurus A, Pictor A and 3C 270. The case of Centaurus A is illustrated in Figures 1 to 3. Figure 1 depicts the source structure with two elongated regions of emission as suggested by Maltby. The rotation of the source with respect to the resolution plane of the interferometer as a function of local hour angle produces the amplitude response variations shown in Fig. 2. The four curves represent four feed configurations, two with the polarizations of the two antennas parallel and two with them perpendicular. Figure 3 illustrates the non-sinusoidal variations in amplitude that can be obtained when parallel feeds are rotated in an interferometer on a resolved source which has structure in its polarization. Each curve in Figure 3 corresponds to a different local hour angle and consequently different resolution.

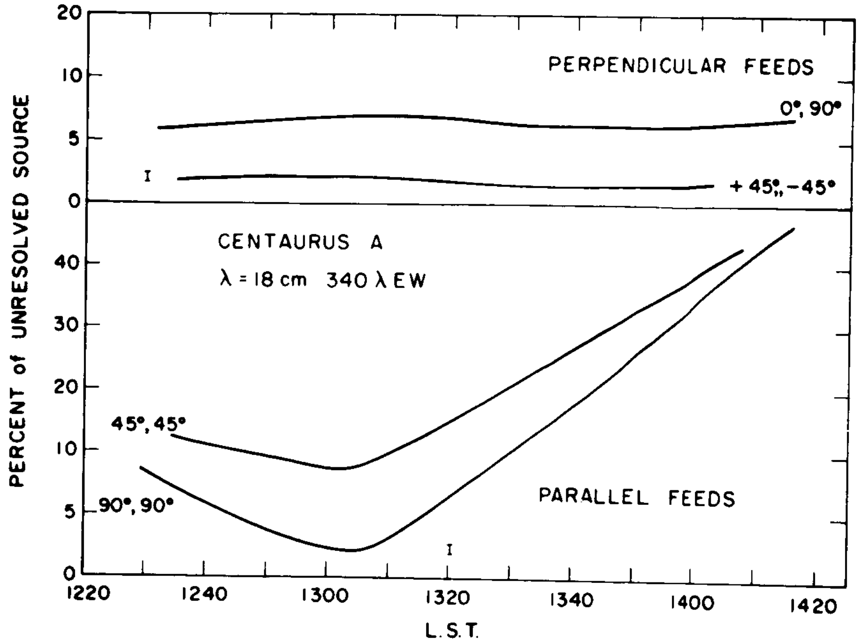


Figure 2.

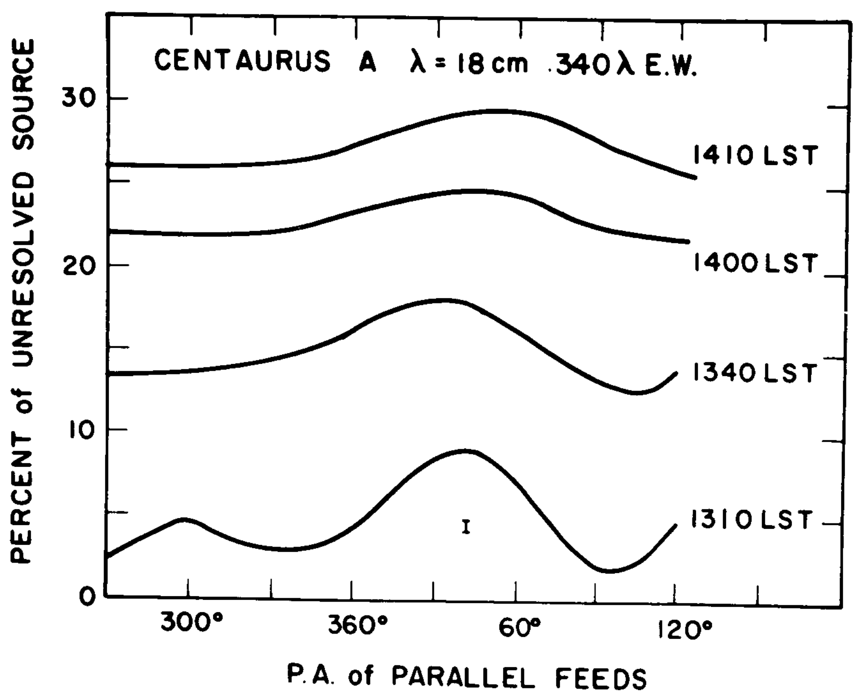


Figure 3.

We must keep in mind when discussing the polarization properties of a radio source that there may be structure in the spatial distribution of both the polarized flux and the position angle of the electric vector, and that further, this distribution may well be a function of the frequency. In order to study such effects, however, one requires either an extremely large antenna (so that its very small beam could be used to actually measure the polarization of individual regions of the source) or else the appropriate equipment for carrying out what we might call "polarization aperture synthesis" measurements. In the latter case, it can be shown that if four times as many measurements are made as would be normally, then in principle the observations enable one to reconstruct the source. Instead of having one number at each point in celestial coordinates (representing the intensity), one would have four numbers giving the intensity, the percentage polarization, the ellipticity and the position angle of the major axis of the ellipse. Unfortunately, such a procedure is at least four times as complicated as the ordinary aperture synthesis measurements, and even they are rarely carried out in full. One tries, in practice, to find simple models and test between Yes and No questions by means of suitable observations.

Such a series of observations is at present in progress and the indications are that in the extragalactic sources Centaurus A, Pictor A, 3C 270, Hercules A and 3C 353 there is a variation of the plane of polarization over the source dimensions. The observations of Cygnus A carried out so far suggest an increase of polarization with resolution, but only measurements at longer baselines will tell. It will then be attempted to fit simple models to the data on all these sources.

Returning to the list of unresolved sources in Table 1 for which the average polarization was measured, we have made only preliminary attempts to derive rotation measures, intrinsic angles of polarization and depolarization rates in the manner of Gardner and Whiteoak. It certainly appears as if the absolute value of the rotation measure is strongly dependent on galactic latitude. The source 3C 286 at 80° galactic latitude is a striking example. The rotation of the plane of polarization between 10 and 21 cm is less than the error in determining the plane at any one of the three frequencies of observation ($\sim 5°$). On the other hand, 3C 111 and 3C 161, both within 10° of the galactic equator, have rotation measures of between 100 and 200 radians per meter^2. To determine the rotation measure without ambiguity for sources with large values, it is necessary to observe at a large number of frequencies, some spaced closely and some widely. This is all important when attempting to determine the intrinsic plane of polarization. It is perhaps just a chance effect that of the seven double sources (3C 33, 3C 98, 3C 111, 3C 273, Centaurus A, Hercules A and 3C 353) for which we had independent measurements to determine the intrinsic plane of polarization, five had intrinsic P.A.'s within 10° of the minor axis of the double sources. Using a larger sample of ten sources (of which six are common), Gardner and Whiteoak seem to find a tendency for the intrinsic plane of polarization to be parallel to the major axis. Many more sources must clearly be studied before reliable statistics are available on this point. It is also possible that high resolution studies of the polarization distribution over the sources will provide a more fruitful approach to the determination of the magnetic field configuration in the radio sources.

DISCUSSION

Schmidt: Are the sources with large rotation measures situated at low galactic latitudes?

Radhakrishnan: Yes, in general, although it is a bit premature to be certain at this time.

Roberts: In addition to the inner Centaurus A source, why not also consider the extended source, which is another double?

Radhakrishnan: We don't really know whether the whole complex should be regarded as one source or whether the extended source represents an older stage in the development of the object. In any case, the other double sources discussed are of comparable dimensions to the central source of Centaurus A, so that it seems reasonable to treat it as being similar to them.

Roberts: If the polarized region of a double source were associated with one of the two blobs, and were of the same angular size as one blob, would this model suffice to explain your results?

Radhakrishnan: Not quite.

N. R. L. Polarization Results

C. H. Mayer
THE E. O. HULBURT CENTER FOR SPACE RESEARCH
U. S. NAVAL RESEARCH LABORATORY

The present paper summarizes observations of linear and circular polarization made with the Naval Research Laboratory 50′ radio telescope during the past few years. The circular polarization measurements were carried out at λ 3.15 cm, and the linear polarization data have been taken at that wavelength as well as $\lambda\lambda$ 3.47 and 9.45 cm.

The observations of linear polarization were made by continuously rotating a linearly-polarized feed at the focus of the antenna. Markers applied to the record indicate the vertical and horizontal planes. A typical record is shown in Figure 1: the upper curve was obtained with the telescope tracking Taurus A at λ 3.15 cm, and the lower curve, which is used as a baseline or reference level, was made with the antenna directed at the sky near the source. The difference between the two curves, which actually were not taken simultaneously, represents the amplitude of Taurus A. There are variations in the baseline of the order of 1°, which, although not very serious in the case of Taurus A, can be quite important for sources like Centaurus A and

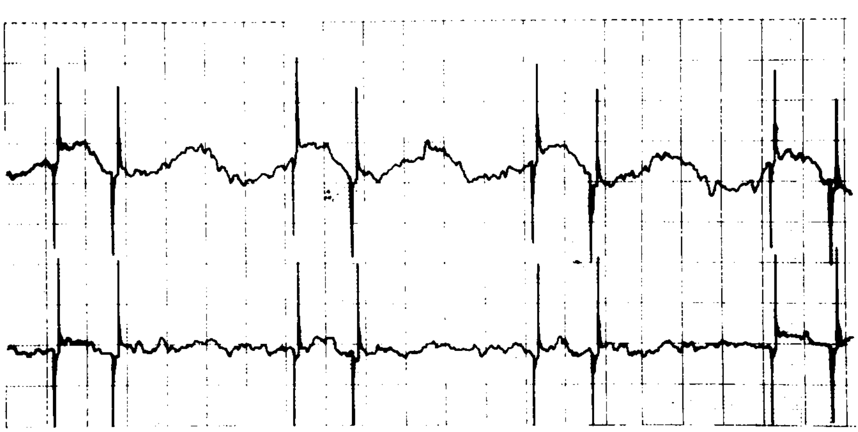


Figure 1.

Virgo A, which themselves have antenna temperatures of only 1° at λ 3.15 cm.

Figure 2 shows some results of the observations at λ 3.15 cm. The attempts to detect linear polarization were successful only for Taurus A, Cygnus A and Centaurus A. In this plot, the data have been adjusted to 0° parallactic angle, corresponding to observations taken with a polar mount. Needless to say, we were rather surprised to measure nearly the same position angle for the electric vector of each of the three sources which gave positive results. However, Figure 3 shows that the actual measured phases were different. The dashed lines indicate the variation of parallactic angle for the measurements taken at different hour angles. This variation is in good agreement with the phase shifts in the records of Taurus A and Cygnus A, and, to a lesser degree, that of Centaurus A.

At λ 3.47 cm, we observed Taurus A, Cygnus A, Cassiopeia A and the Orion Nebula. The results were quite similar to those found at λ 3.15 cm.

Figure 4 summarizes our λ 9.45 cm work. The results were

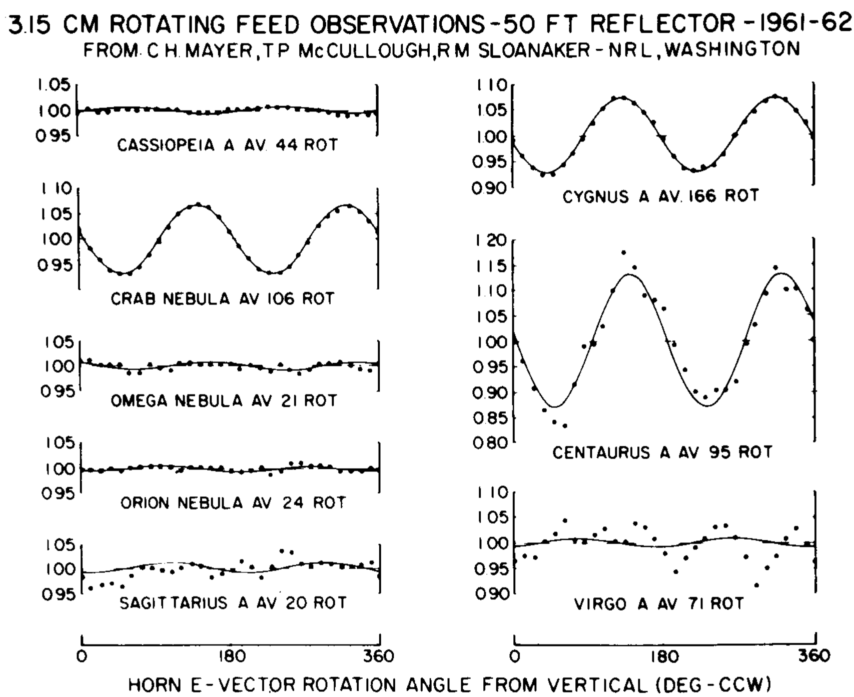


Figure 2.

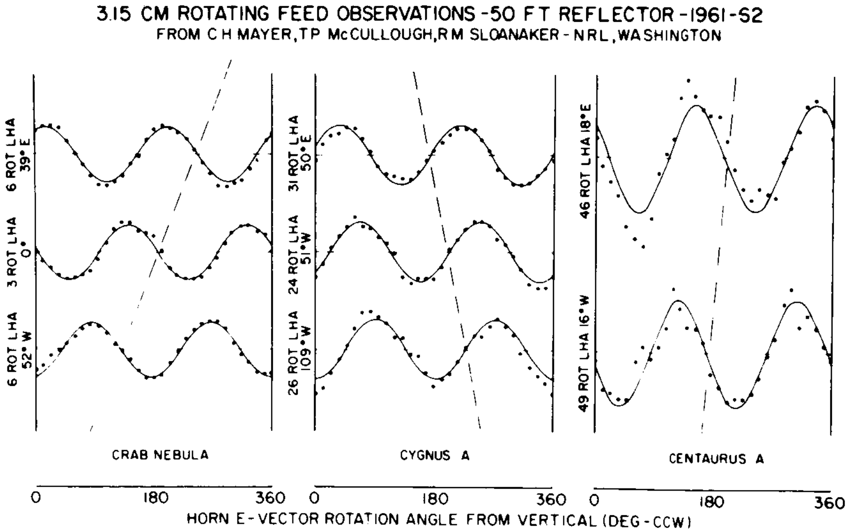


Figure 3.

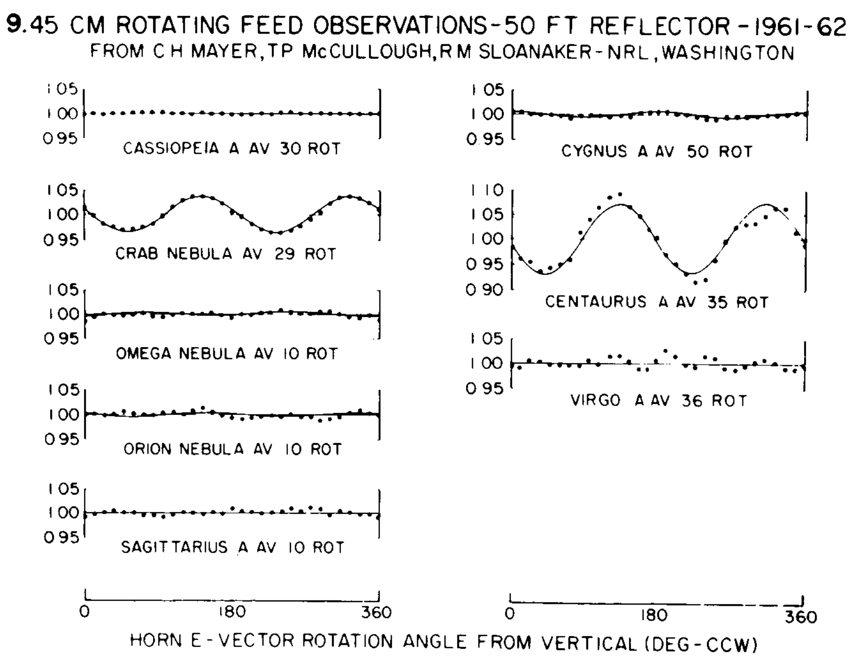


Figure 4.

positive for Taurus A, Centaurus A and Cygnus A, but the Cygnus A observation is regarded as marginal.

The present results both verify previous N.R.L. work and also include our first positive measurements of Cygnus A and Centaurus A. Table 1 is a comparison of present and past N.R.L. polarization observations on eight well-known sources. In general, the agreement between measurements made at different times and with different antennas is gratifying. Except for a small discrepancy in the position angle for Taurus A at λ 3.15 cm, as measured at various times in the interval 1956-1962, there is no indication of any changes in the measured polarization with time or equipment.

Figures 5, 6, and 7 are comparisons of our observations with those data of other groups which were available prior to this meeting. In the case of Taurus A (Figure 5), the total Faraday rotation seems to be rather small. The N.R.L. receiver accepted radiation in two bands, separated by roughly 100 Mc/s. For small total rotations such as that found for Taurus A, the depo-

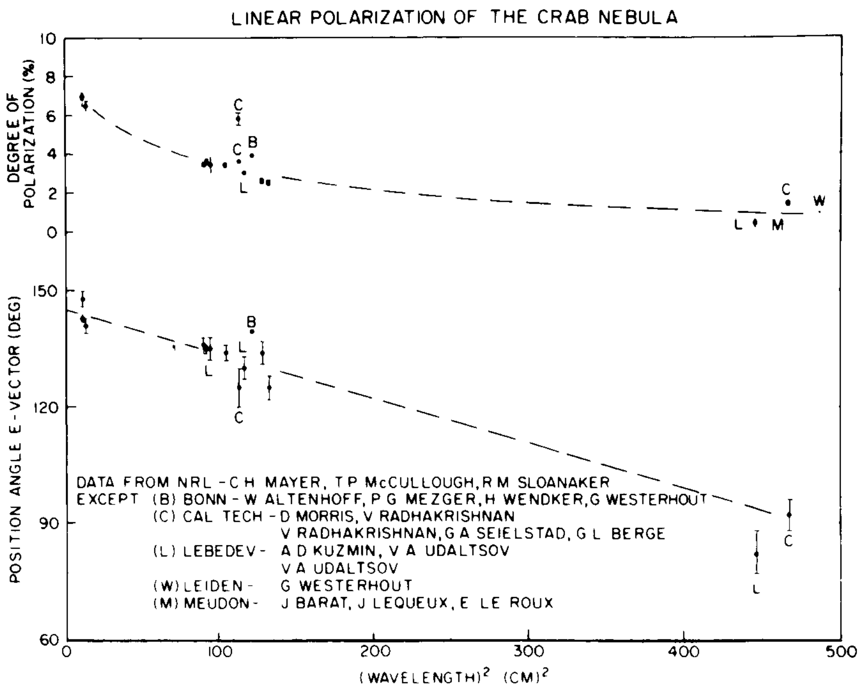


Figure 5.

TABLE 1—SUMMARY OF LINEAR POLARIZATION MEASUREMENTS
From C.H. Mayer, T.P. McCullough, R.M. Sloanaker—Naval Research Laboratory, Washington

		Crab Nebula	Cygnus A	Centaurus A	Cassiopeia A	Virgo A	Omega Nebula	Orion Nebula	Sagittarius A
Rotating Linear Polarization									
50 Foot Reflector—1961-62									
3.15 cm	P	7.0±0.1 (P.E.)	7.5±0.2	13.5±1	<0.5	<1	<1	<1	<1
	θ	143±1	143±2	144±3					
3.47 cm	P	6.5±0.1	7.0±0.4	---	<0.5	---	---	<1	---
	θ	141±2	141±3						
9.45 cm	P	3.7±0.1	0.5±0.2	7.2±0.5	<0.5	<0.5	<0.5	<0.5	<0.5
	θ	135±1	170±10	121±3					
84 Foot Reflector—1960									
9.4 cm	P	3.5±0.1	<1	---	<1	<2	---	---	<2
	θ	136±2							
84 Foot Reflector—1958									
10.2 cm	P	3.5±0.1	<1	---	<1	<3	<1	---	---
	θ	134±2							
11.3 cm	P	2.7±0.1	<1	---	<1	<5	---	---	---
	θ	134±3							
11.5 cm	P	2.6±0.1	<2	---	<2	---	---	---	---
	θ	125±3							
50 Foot Reflector—1957									
3.15 cm	P	7±0.5	---	---	<2	---	---	---	---
	θ	148±2							
Fixed Linear Polarization									
50 Foot Reflector—1956									
3.15 cm	P	~9	---	---	---	---	---	---	---
	θ	~140							

P = Degree of linear polarization (%). θ = Position angle (°) of electric vector.

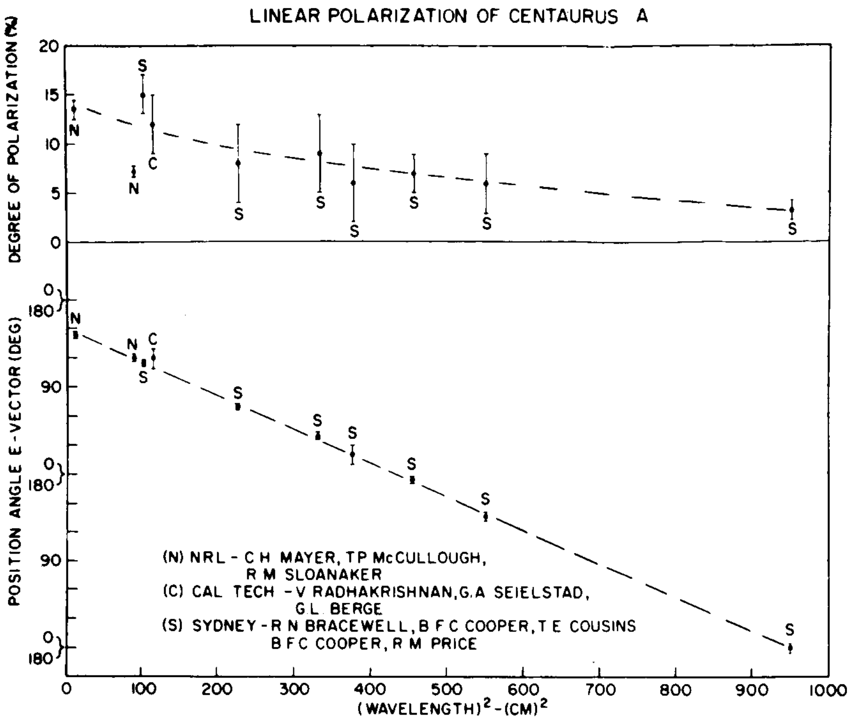


Figure 6.

larization due to the differential rotation between the two channels will be insignificant. Figure 6 shows that the total Faraday rotation is also small for Centaurus A.

For Cygnus A (Figure 7), the data are two few to allow us to draw any conclusions. In fact, we do not know where to plot the λ 9.45 cm position angle with reference to those measured at $\lambda\lambda$ 3.15 and 3.47 cm. Two possible positions for this point are shown in the figure. In order to resolve this question, observations are being made with J. P. Hollinger and R. A. Mennella in the 5 to 6 cm wavelength region, and we hope very shortly to be able to determine the amount of rotation for Cygnus A. Once this is done, we will be able to find the amount of bandwidth depolarization which occurs in our existing observations of this source.

Together with J. P. Hollinger and P. J. Allen, we have made some preliminary attempts to detect circular polarization at λ 3.15 cm in the same eight sources listed in Table 1. At the present time, we can set an upper limit of 5% to the circular polarization at this

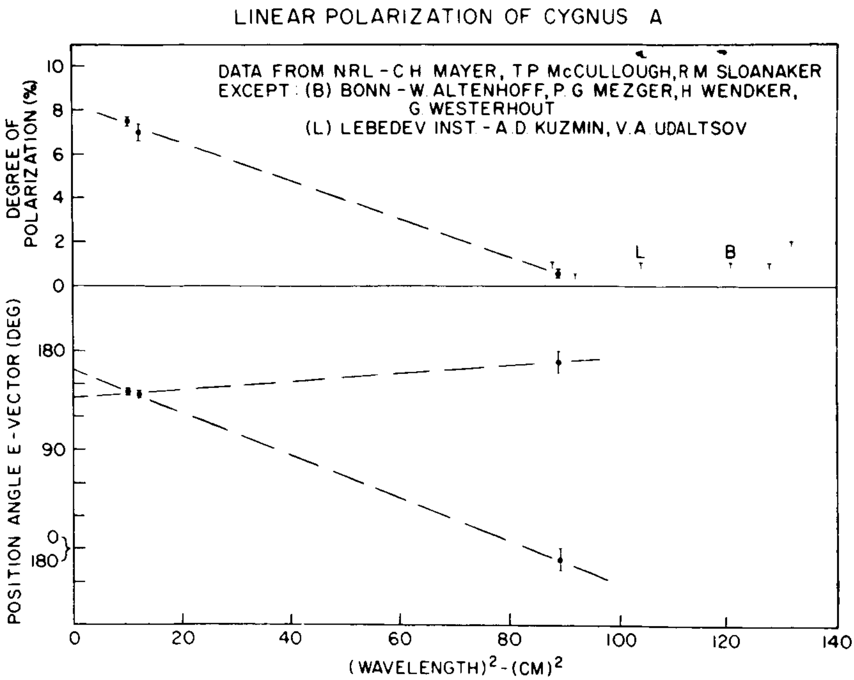


Figure 7.

wavelength in any of these sources; however, future work will enable us to refine this value considerably. *(1)*

The author is grateful to V. Radhakrishnan, G. A. Seielstad and G. L. Berge for communicating their results prior to publication.

[1] See Ap.J. *137*, 1309 (1963).

Recent Polarization Work at Jodrell Bank

R. G. Conway
NUFFIELD RADIO ASTRONOMY LABORATORIES
JODRELL BANK

Some recent measurements of linear polarization in ten discrete radio sources, made by Davies and Shuter with the 250′ telescope at Manchester, are summarized in Table 1. The observations were taken at λ 21 cm, using part of the equipment which was developed for measuring the Zeeman effect in the Hydrogen line. The receiver bandwidth was increased to 5 Mc/s for making these polarization observations; the dish was fed by a waveguide feed containing two perpendicular probes.

The whole feed can be rotated, so that after making an instantaneous measurement of the flux density at P.A. 90° minus the flux density at P.A. 0°, one can then measure the difference in the flux densities at the P.A.'s 135° and 45°. From these quantities one obtains the magnitude and polarization angle of the linearly polarized component.

Much of the optical data which appear in Table 1 was supplied by CalTech. The radio diameters are obtained from Palmer. None of the polarization data have been corrected for Faraday rotation, but an instrumental polarization of a few per cent, which produces an apparent polarized component which is proportional to the flux density, has been subtracted in all cases.

The data have been correlated against a number of parameters, and in particular against the spectral information. Figure 1 shows the distribution of the sources on a plane in which per cent polarization is plotted against the quantity ρ, which is defined in the author's earlier paper (this volume). The point for Cygnus A represents Mayer's λ 3 cm observation, and the point for 3C 270 shows the Australian result. The data for Centaurus A have been processed so that they represent this source as it might appear from a distance such that it would not be resolved by the 250′ telescope. Of the four so-called "radio stars" shown, 3C 48, 196, 273 and 286, two have rather high polarization, and of the three core and halo sources, 3C 84, 218 and 274, two show rather low

Table 1.

The percentage polarization and position angle of the electric vector for 10 sources measured at 1410 Mc/s at Jodrell Bank

Source	Polarization (%)	Position Angle (°)	Identification	Distance (Mpc)	Comments
3C 48	1 ± 1	70 ± 10	"Star"	—	Diameter less than 1" at 160 Mc/s.
3C 84 (Perseus A)	5 ± 1	36 ± 10	NGC 1275 Two spiral galaxies	53	Appears to be a core and halo at radio frequencies.
3C 123	4.5 ± 1.5	8 ± 10	—	—	2 components 12".5 apart; E.W. component size 5".3.
3C 196	10.0 ± 0.5	49 ± 2	"Star"	—	Diameter $\simeq$ 5".
3C 274 (Virgo A)	< 0.5	—	NGC 4486	12	Core and halo at radio frequencies associated with elliptical and jet.
3C 286	12 ± 1.5	31 ± 2	"Star"	—	Diameter $\simeq$ 1".
3C 295	6.0 ± 1.0	162 ± 4	$20^m.9$ galaxy	1380	2 components 4" apart; component size ~1".7
3C 348 (Hercules A)	2 ± 0.5	6 ± 5	19^m galaxy	460	2 components 1".95 apart; component size ~0".75.
3C 353	6 ± 0.5	7 ± 10	$16^m.8$ galaxy	(250)	2 unequal components, 2'.5 apart; component size ~1'.4.
3C 405 (Cygnus A)	< 0.5	—	$15^m.3$ galaxy	170	2 components 1'.58 apart; component size ~ 0'.7.

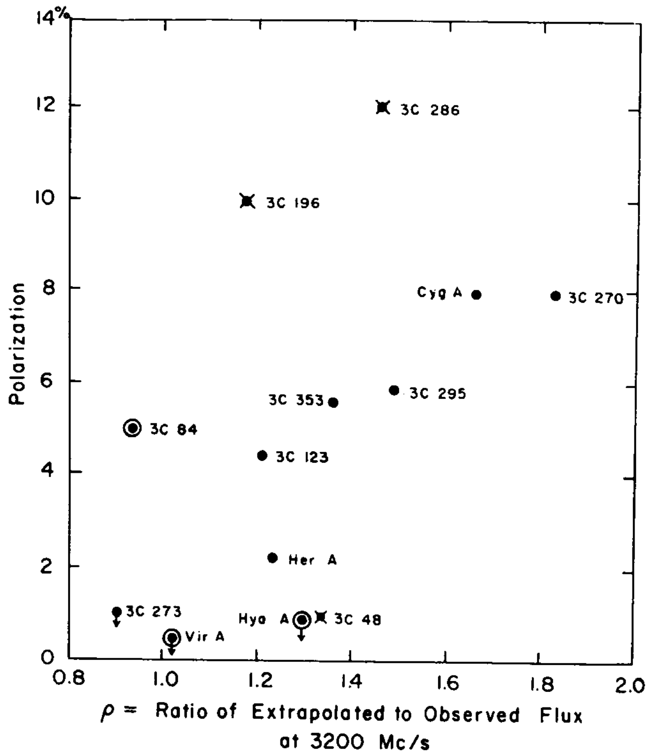


Figure 1.

polarizations. Obviously, the statistics are too small to enable any conclusions to be drawn.

Figure 2 is a plot of per cent polarization against redshift for sources known to be extragalactic. No correlation is evident.

The Jodrell Bank measurement of 3C 295 shows that it is linearly polarized at λ 21 cm. This result, together with the λ 10 cm N.R.L. observation, indicates a differential Faraday rotation

$$\Delta F < \frac{\pi}{2} \text{ radians,} \tag{1}$$

since otherwise the source would be completely depolarized. Further, it appears that the total Faraday rotation along the line of sight between 3C 295 and the Earth may be less than about 3 rotations, in which case

$$\overline{Bn_e} < 10^{-13} \text{ gauss/cm}^3 \tag{2}$$

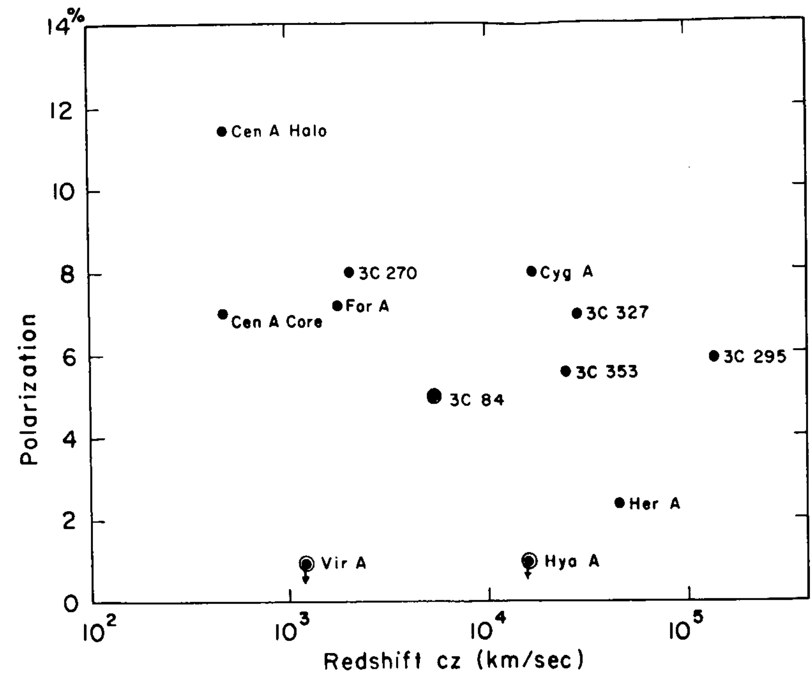


Figure 2.

in intergalactic space. According to the version of the steady-state theory in which matter is created in the form of protons and electrons,

$$B \sim 10^{-6}$$
$$n_e \sim 2 \times 10^{-5} \qquad (3)$$

which lead to a Faraday rotation which is two orders of magnitude greater than that suggested by the 3C 295 observations.

DISCUSSION

Roberts: Why isn't F given directly by comparison of the measurements at $\lambda\lambda$ 10 and 21 cm?

Conway: In the absence of measurements at an intermediate wavelength, the observed difference in position angle may be interpreted as 6°, 186°, 366°, etc. But it is unlikely to exceed a few rotations.

Editors' Note: The following table summarizes the comparison of λ 21 cm polarization measurements, made at Jodrell Bank, CalTech and Sydney, which evolved in discussion among Drs. Conway, Radhakrishnan and Roberts, after the presentation of the above paper. *The data are preliminary.*

Table of % Polarization and Position Angle at λ 21 cm

	Jodrell Bank		CalTech		Sydney	
	% Pol.	P.A.(°)	% Pol.	P.A. (°)	% Pol.	P.A.(°)
3C 48	1. ± 1.	70. ± 10.	0.7 ± 0.5	160. ± 30.		
84	5. ± 1.	36. ± 10.	0.8 ± 0.5	37. ± 17.		
123	4.5 ± 1.5	8. ± 10.	0.5 ± 0.2	68. ± 10.		
196	10.0 ± 0.5	49. ± 2.	0.4 ± 0.4	155. ± 30.		
286	12. ± 1.5	31. ± 2.	P 9.2 ± 0.4	31.5 ± 5.		
295	6.0 ± 1.0	162. ± 4.	0.5 ± 0.3	160. ± 15.		
348	2. ± 0.5	6. ± 5.	P 1.4 ± 0.2	59.	2. ± 0.5	59.
353	6. ± 0.5	7. ± 10.	P 2.9 ± 0.2	0. ± 5.	3.0 ± 0.6	171. ± 5.

(Observations marked "P" are considered positive indications of linear polarization by the CalTech group.)

Linear Polarization of Discrete Radio Sources by Use of a 9.4 cm Maser

William K. Rose*†
COLUMBIA RADIATION LABORATORY
COLUMBIA UNIVERSITY
AND
E. O. HULBURT CENTER FOR SPACE RESEARCH
U. S. NAVAL RESEARCH LABORATORY

The purpose of these remarks is to briefly describe 9.4 cm polarization measurements of six radio sources: 3C 48, 3C 147, 3C 286, 3C 295, Hercules A and 3C 433. The observations were made by the author in collaboration with J. M. Bologna and R. M. Sloanaker during July-October 1962. The amplifier used throughout the experiment was a solid state maser amplifier which was at the focus of the Naval Research Laboratory 84′ radio telescope. The output noise fluctuation level of the maser was 0.013°K for a 7 second intregation time. Figure 1, which is typical of the records obtained, is a drift curve of the very distant radio source 3C 295. An Argon noise source whose equivalent temperature is 0.48°K referred to the system input was used as the calibration signal and was turned on before and after each drift curve as shown in Figure 1.

Figures 2 and 3 summarize the results of our measurements. The probable errors are approximately ±1.5% for the uncertainty in the measured degree of polarization and ±10° for the measured uncertainty in the electric field vector position angle for the maximum intensity. Our data for 3C 286, Hercules A and 3C 433 are in good agreement with recent observations carried out at the California Institute of Technology.

By measuring the degree of polarization and the position angle of the electric field vector for maximum intensity at more than

---

*Supported by the Office of Naval Research, the U.S. Army Signal Corps, and the Air Force Office of Scientific Research.

†Now at the Princeton University Observatory, Princeton, New Jersey.

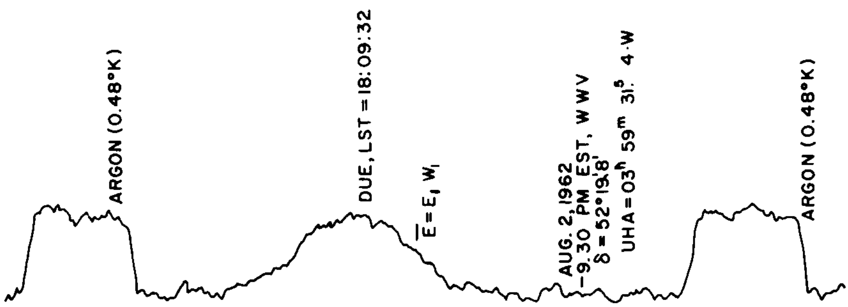


Figure 1.

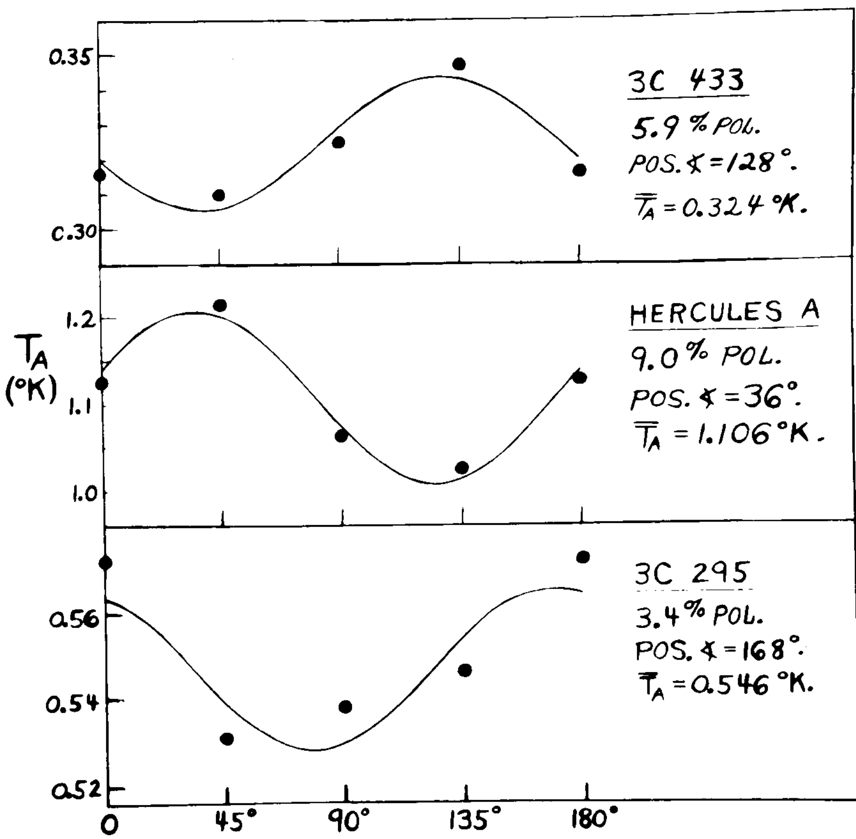


Figure 2—Position Angle of Horn E-Vector.

one frequency we can obtain an upper limit for the product of the number of electrons/cc in intergalactic space times $H_{||}$, the average component of the intergalactic magnetic field along the line

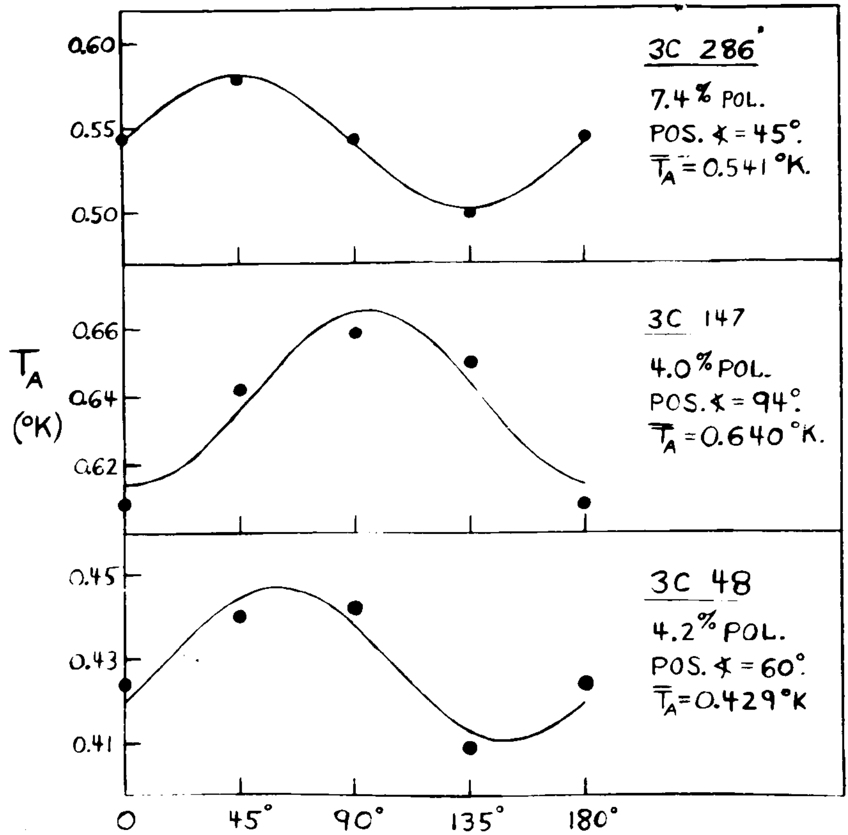


Figure 3—Position Angle of Horn E-Vector.

of sight. We assume that intergalactic space is divided into regions of approximately uniform magnetic field of characteristic length L and that there are many such regions between ourselves and the radio source in question. In addition, we assume that the distance to Hercules A and 3C 433 is 6×10^8 parsecs and that the source diameters are 10^5 parsecs and 5×10^4 parsecs respectively. We have used the California Institute of Technology 21 cm measurements reported at this conference and our own at 9.4 cm to arrive at the following upper limits on the basis of the above assumptions:

Source	Electrons/cc in intergalactic space $\times H_{\|}$ in gauss
Hercules A	$\leq 4 \times 10^{-12}$
3C 433	$\leq 2 \times 10^{-12}$

If future high resolution radio measurements show that these sources are not appreciably polarized over regions as extensive as those suggested above, these upper limits will have to be corrected accordingly.

Radio Properties of Identified Extragalactic Sources

T. A. Matthews
OWENS VALLEY RADIO OBSERVATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

Identifications with extragalactic objects exist for about 57 extragalactic radio sources.[1] This includes six spiral galaxies but omits other spirals which have been observed only at one frequency. The 51 sources identified with non-spiral objects belong to the group of strong radio emitters.

The distance was determined for each source from radial velocity measurements when available. These measurements have been made mainly by M. Schmidt. The distance for each spiral has been estimated from the observed diameters of H II regions, or from other standard indicators by A. R. Sandage. For the non-spiral galaxies when no radial velocity measurement was available, an absolute magnitude of $M_{pg} = -20.5$ was assumed.

In most identified extragalactic sources, the centroid of the radio emission falls near the position of the optical object, often within one-tenth of the radio diameter. In many cases the difference in position is less than the quoted error in the determination of the radio centroid. However, there are at least some sources for which the displacement of the radio centroid from the optical is a significant fraction of the radio diameter. Some examples of displaced sources are 3C 33, 40, 75, 227, 264, and 465. In four cases either the available radio description of the source is incomplete, or there is a distinct possibility that additional galaxies are involved with the radio source. However, the radio centroids of 3C 33 and 3C 227 are well determined and are definitely displaced from the galaxy. On the other hand, there is a strong selection effect due to the fact that good positional agreement is usually required before an identification is regarded as secure; thus there may be quite a few more sources which have such displacements. If such a displacement occurred in a distant

[1] This number of identifications pertains to December, 1962. By December, 1963, the number had increased to 100 identified sources.

cluster, it would be difficult to identify the parent galaxy from positional data alone. Additional information on the galaxy types and on the presence or absence of strong optical emission lines would probably allow the unique object to be selected.

Based on the distance estimates from the optical observations, linear projected radio diameters have been computed and are found to range from 600 to 480,000 parsecs. Further, the radiated power, L, has been calculated assuming a flux density spectrum which follows the simple power law,

$$S \sim \nu^{-\alpha}$$

between upper and lower frequency cutoff limits. Estimates of the spectral index and cutoff frequencies for each source were based on the data of Conway, Kellermann and Long (1963). The cutoff frequencies were estimated from the observed curvature in the [$\log S - \log \nu$] plot for each source. If a source shows no curvature in that plot, the cutoffs were taken as 10^7 c/s and 10^{11} c/s. The high frequency cutoff may be an underestimate in some cases, since the highest frequency point of a spectrum observed as linear must be at least a factor of ten below the true upper cutoff frequency. Although this approach is rather rough, it was felt to give reliable relative values for L.

The radiated power, L, is plotted against the radio diameter in Figure 1. The radio structure of each source is also indicated. The central and outer sources of Centaurus A, a "double-double," are connected by a solid line in the figure, as are the components of the halo-core sources and also the three components of Hydra A.

A selection effect is introduced by the fact that an interferometer responds progressively less as the source diameter increases with respect to the lobe spacing and as the flux decreases. The dotted line in Figure 1 is an approximate representation of the limiting surface brightness to which the CalTech interferometer gives reliable results; it corresponds to

$$d = 15'$$
$$S = 3 \times 10^{-26}\ \mathrm{W/m^2\,(c/s)}$$

at a frequency of 960 Mc/s. This curve is also roughly appropriate to the 3C survey. Of course, a single-dish antenna or a fan beam array will not be limited in this way. On the other hand, they will be affected by confusion and variations in the background. Thus, few, if any, sources below the dashed line will be

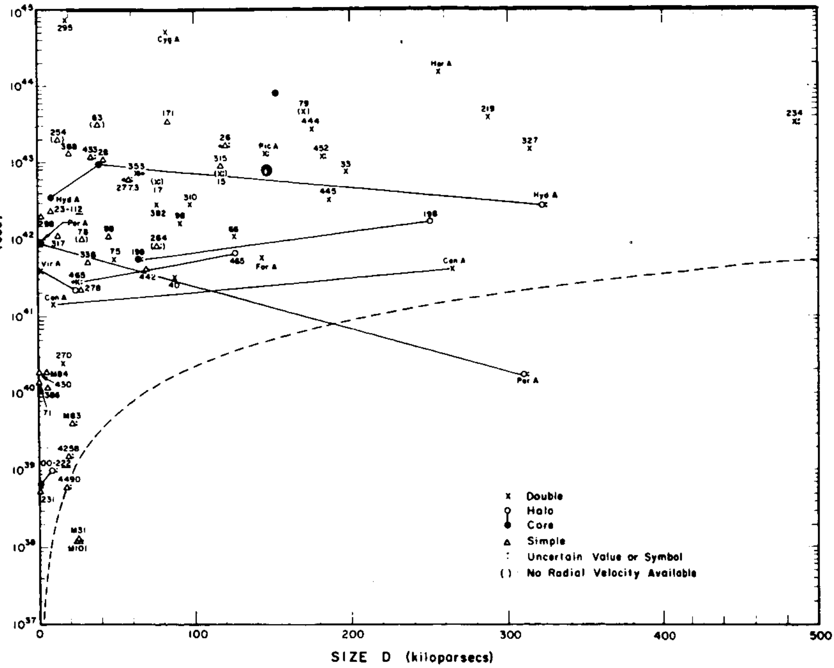


Figure 1.

observed. Another selection effect arises from the fact that the optical material on which most identification attempts have been based is limited to galaxies brighter than $m_{pg} \approx 18$. This arises because only 48″ Schmidt plates have been available for most identifications. Thus, there is a general cutoff near $L \approx 10^{44}$ erg/sec, where most of the galaxies identified are of about 18.5 apparent magnitude. Finally, the present group of identified sources is not a valid statistical sample because, in order to secure as many examples as possible, any identification has been accepted irrespective of its apparent flux. As yet we cannot discuss the identifications for sources brighter than some limiting apparent radio flux.

Sources having $L < 10^{40}$ erg/sec are all normal spirals or irregular galaxies, while those having $L > 10^{40}$ erg/sec are ellipticals or related types of galaxies. The double sources are in general larger than the single ones. Their separations range from 1.8 to 480 kiloparsecs. The luminosities of these sources range from 10^{40} up to nearly 10^{45} erg/sec. The core of M87 is the smallest known double source.

The smallest measured simple source, NGC 1068 (= 3C 71) has a diameter of 600 parsecs, but others are as large as 120 kiloparsecs. Their luminosities range from 1.2×10^{40} to 3.5×10^{43} erg/sec. Presumably, 10% to 20% of the double sources will be viewed end-on and will appear to be single. However, this will not account for all the single sources, especially when it is realized that the identifications made to date have tended to favor the apparently large diameter sources. Thus some sources, at least, are smaller than their associated galaxies. For example, the NGC 1068 source is very probably single, and appears to be confined to the nuclear region of that galaxy. Also, the diameter of the radio source in M82 is of the order of one-tenth the optical diameter of the galaxy.

The recently discovered quasi-stellar objects are not plotted in Figure 1, but the three which have known distances (3C 47, 48, 273) all have values of L slightly less than that of Cygnus A. Thus they are among the most luminous sources. If 3C 286 has a z of 0.86, as Shklovsky has suggested, but which is unconfirmed since only one line is known, then its L is about 5×10^{45} erg/sec, with a diameter of about 260 Kpc. This would be the most luminous radio source known.

It is interesting to note that the average separation of the members of a rich cluster of galaxies is about 100 kiloparsecs, whereas some of the radio diameters are as large as 500 Kpc. Thus other galaxies are, or have been embedded in the radio emitting regions, yet no sign of interaction is apparent. The parent galaxy seems to dominate the intergalactic space in the cluster. Quite a few of the presently identified sources are smaller than the parent galaxy, a comparable number have roughly the same diameter as the galaxy, and a few appear to extend far beyond the detectable optical limits and thus probably are not now physically associated with the parent galaxy.

When a radio source is found to occur in a cluster of galaxies, the galaxy with which it is identified is usually found to be the optically brightest, by several magnitudes, and the largest of the cluster members. When there are several sources, as in the Virgo cluster, the weaker radio sources are intrinsically very weak and are associated with galaxies which are considerably fainter optically than the prime source.

The existence of the "double-double," Centaurus A, and other halo-core objects suggests that a galaxy may produce more than one radio source during its lifetime. Presumably a source begins as a small emitting region near the nucleus of the galaxy, and in fact the observed small-diameter sources are all embedded in their associated galaxies. In time the source grows larger. Some of them blow up like balloons; others apparently channel their energy into two directions, creating two emitting regions which move outside of the galaxy and eventually become well separated from it. This difference in structure may be the result of generally weak magnetic fields for the single large sources, and a much stronger aligned magnetic field providing the necessary channeling for the double sources. There must be some quite old sources which, having exhausted most of their energy, lie in the unobservable region of low surface brightness, below the dotted curve of Figure 1. Objects such as the extended halo of Perseus A, which was studied with a fan beam by the Cambridge group, may belong to this category.

Optical Observations

The Identification Problem*

R. Minkowski
RADIO ASTRONOMY LABORATORY
UNIVERSITY OF CALIFORNIA, BERKELEY

N65 13260

It has been clear for some time now that the difficulty in finding the optical objects which are associated with radio sources is mostly due to the inaccuracy of the available radio positions. During roughly the last two years, however, considerable improvement has been achieved in the accuracy of radio positional data and consequently definite progress has been made on the identification problem.

At the I.A.U. Berkeley meeting, a group of astronomers suggested that it would be desirable to prepare a list of reliably determined radio source positions and the author was saddled with that task. Many workers responded to our request for advance information on unpublished observations; in this connection we are indebted to Drs. Hanbury Brown, Greenstein, Hazard, Joshi, Matthews, Palmer, Ryle and Schmidt.

Most of the work which led to the more precise positions which are now available consisted not of independent source surveys, but rather of reinvestigations of sources selected from previous catalogues, especially the 3C and, to some extent, that of Mills, Slee and Hill. As a result of this work, a fairly substantial number of high precision positions were obtained. A comparison of these positions with the positions of definitely identified sources, and intercomparison between the positions found by different observers, makes it possible to estimate the real accuracy of these positions. The errors in position are generally found to be distributed normally, which means that they have the significance essentially of mean or probable errors.

For the CTC source list of CalTech, this study leads to the following results. The probable error in right ascension is about ± 0.5 sec and, in addition, there is a systematic error, possibly a function of R.A., of the order of 0.6 sec. The p.e. in declination is about $\pm 10''$, although one should note that the declination errors are not normally distributed.

*This report presents the status as of November, 1962. No changes have been made to bring it up to date.

Examination of revised 3C positions measured by Elsmore at Cambridge reveals that the p.e. in right ascension between 0 and 15 hours is about ±0.5 sec, while between 15 and 24 hours it is of the order of ±1. sec. In addition, there seems to be a systematic error of equal magnitude. The p.e. in declination is about ±1′.5.

Of the positions measured by Joshi at Meudon, about 75 per cent of the right ascensions have a p.e. of approximately ±0.5 sec, but the remaining 25 per cent are in error by amounts from −3 to −4 sec in a way that may depend on the R.A. Apparently, these positions are not entirely reliable. They seem to be either correct or noticeably wrong. The p.e. in declination is about ±1′.

From this material, 53 extragalactic objects, as well as several of the so-called "radio stars" (which may also be extragalactic) have been identified. If this is compared with information available two years ago, it would seem as if very little progress has been made. In 1960, Mills published a list of 30 probable identifications, and some time later at the U.R.S.I. meeting in London, Bolton presented a list of 29 identifications. Of these, nine sources were common to both lists, resulting in 50 distinct identifications.

It is now clear however, that quite a few of these identifications were spurious. This is understandable for sources from the survey of Mills, Slee and Hill, since the errors in the positions are relatively large, as a consequence of the large Mills Cross beam width (~ 50′). These errors can be as great as 0.4 min in R.A. and 10′ in Dec.

Of the 30 identifications suggested by Mills, 12 are now confirmed, 10 are rejected and 8 cannot be definitely accepted or rejected due to lack of more recent radio positions of high precision. Of the 29 identifications listed by Bolton, 22 are definitely acceptable and 7 are rather doubtful, as shown by more recently obtained radio positions.

Using the sources identified by Mills and by Bolton, the writer attempted in 1961 to develop statistical samples from which the luminosity function of extragalactic sources could be determined. The treatment is obviously no longer valid for the identifications with MSH sources. However, as far as the sources discussed by Bolton are concerned, the study remains fully valid because the seven identifications which were rejected were not, as it happens, included in the statistical sample, for reasons such as intensity or position in the sky. The expression for the luminosity function thus remains nearly the same, namely:

$$\log n\ (M) = 6.9 + 0.48\, M_r \tag{1}$$

where n (M) is the number of sources per cubic parsec with absolute magnitude M in an interval of one magnitude, and M_r is the absolute radio magnitude based on the following definition of apparent radio magnitude:

$$m_r = -53.4 - 2.5 \log S_{158\ \mathrm{Mc/s}} \qquad (2)$$

The writer prefers to argue in terms of radio magnitude, rather than in total energies, because the former is an observed quantity. Total energies, although quite important from several points of view, depend upon the spectral distributions, which are not completely known.

Observations of optically bright galaxies constitute the second set of material to be considered. Few optically bright galaxies have been found in general radio surveys; rather the majority of those detected were found by deliberate searches for radio sources in the vicinity of such galaxies. This procedure has the disadvantage that a faint random source could easily be confused with a nearby bright galaxy. The historic example of this was the original identification of 3C 295 as Messier 101.

As of the present time, a total of 60 bright galaxies have been examined by Hanbury Brown and Hazard in Manchester, Miss Leslie in Cambridge and Mathewson in Parkes. Of these, 30 were found by at least two observers to be detectable radio sources. This makes a total of 83 known extragalactic sources, not counting "radio stars." In addition, a number of sources observed by Bolton with the 210′ dish at Parkes may lead to identifications. Since no instrument like the 48″ Schmidt exists in the southern hemisphere, identifications must be made with the 74″ telescope, a rather slow and complicated process.

There are also a number of positions which will result from the work of Scheuer, who has investigated the so-called extended Mills sources. It turns out that some of them do not exist and others are really blends of several sources. In two or three cases, resolution of the components of a blended source leads to separate identifications. However, the optical investigation of these sources has not yet been completed, and therefore they are omitted from the statistics of the present study.

The 3C catalogue, although not an absolute statistical sample, has been the basis for much identification work. It lists 471 sources of which 56 have been identified. Of these, 44 are extragalactic, five are supernova remnants, two are H II regions, and five are "radio stars." Examining the extragalactic identifications, we find that for flux densities down to 50×10^{-26} W/m^2 (c/s), the percentage of sources which have been identified is very high. In fact, of those sources down to this flux level which can in principle be identified, close to 100 per cent have been identified. Of course, sources which lie in heavily obscured regions cannot be identified. The corresponding numbers representing the percentages of 3C sources identified for flux densities in various other intervals are given in Table I.

Table I

Flux density (W/m^2 (c/s))	Per cent identified
$50 - 40 \times 10^{-26}$	50
$40 - 30$	21
$30 - 20$	11
$20 - 10$	1

The percentage of identified sources drops sharply at about 30×10^{-26} W/m^2 (c/s) because precise positions for these fainter sources have not yet been determined. These percentages are very low indeed compared to what may be eventually achieved. Making a cumulative count, one finds that for flux densities greater than 25×10^{-26}, 68 per cent of the 3C sources have been identified and for sources brighter than 15×10^{-26}, 36 per cent have been identified. Considering that these percentages must be lower limits, due to the inadequacy of the positional data, they are in reasonable accord with the derived luminosity function.

We now turn to the question of how many "radio stars" exist. This cannot be answered very precisely. Information from the interferometric investigations of sources, such as that conducted by Palmer at Manchester, reveals that of the four "stars" 3C 48, 147, 196 and 286, only two are probably really point sources: 3C 48 and 147 are unresolved at an interferometer spacing of 61,000 wavelengths, while 3C 196 and 286 apparently begin to be resolved at 32,000 λ, or perhaps somewhat less. A fifth "star," 3C 273 has been resolved into two components by the method of lunar occultation.

From Palmer's data, one can surmise that at least a dozen, and possibly even 20 more sources may be "stars." This is, nevertheless, a small percentage of the 471 3C sources.

The fact that many sources are double, that is, consist of two lobes, complicates the identification problem. About 32 per cent of the sources observed by Maltby and Moffet are double. The usual but arbitrary assumption that the centroid of the two lobes should coincide with the optical object seems justified by the fact that many objects identified in this manner show optical spectra which are remarkable for the presence of strong emission lines.

In some cases, the precision of the radio positions has led to complications. Figure 1 shows an example of this type of situation, the source 3C 75. Its flux at 400 Mc/s is 14.5×10^{-26} W/m^2 (c/s), according to Conway, Kellermann and Long. The abbreviations used in the figure are as follows:

MSH	Mills, Slee and Hill
CTA	CalTech single dish survey (Harris and Roberts)
E, 3C Rev	Revised Elsmore position, listed in the Revised 3C Survey (Bennett)
J	Joshi
CTC	Unpublished CalTech list

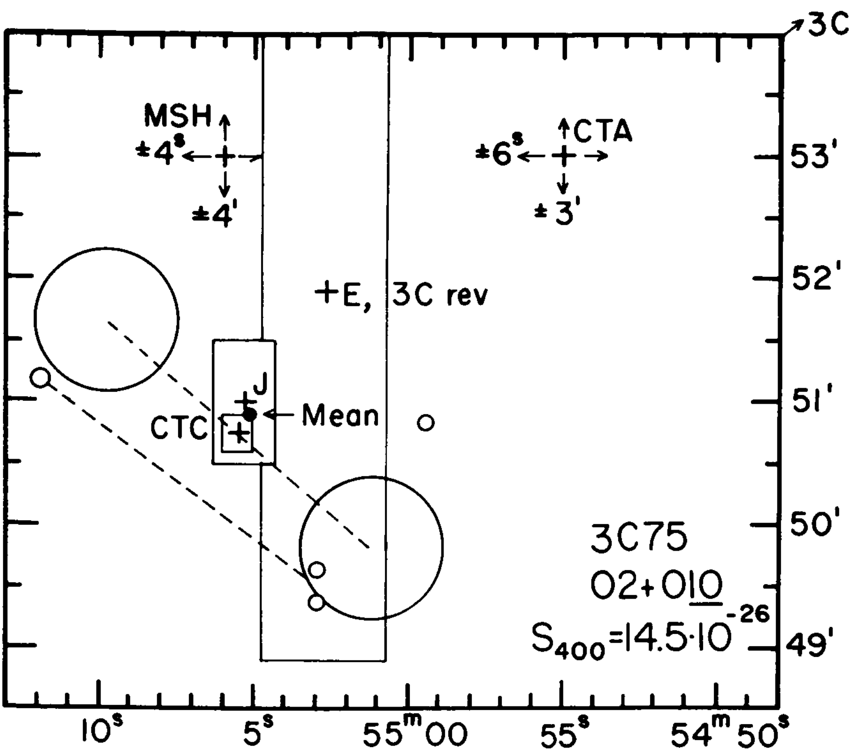


Figure 1—Measured positions of 3C 75.
Abscissa = R.A. — 2ʰ
Ordinate = Dec. — 5°

The accuracy of the MSH position is rather low. On the basis of it, an identification with a roughly 13th magnitude double galaxy was originally suggested. The original 3C position needs to be lobeshifted and then corrected in declination.

All of these positions for 3C 75 are in agreement in the sense that their differences in one coordinate are never large compared to the sum of the quoted errors. Taking the weighted mean of the measurements, one obtains the position shown by the dot, which of course agrees best with the two most precise positions.

The source has been analysed into two components, represented by the two larger circles. The double galaxy is clearly not a satisfactory unique identification. There are several other galaxies which might contribute to the source; however, none of these is very satisfactory by itself. The situation is complex because 3C 75 is in the direction of a cluster of galaxies, Abell 400, and may well be associated with more than one of the galaxies.

A similar situation exists for several other extragalactic sources, including 3C 40 and 66, which are located in A 194 and 347, respectively, and also MSH 21-2*1*, which is located in a small cluster or group of galaxies not listed by Abell. This difficulty probably is connected with the fact that there is a correlation between radio sources and clusters of galaxies in the sense that the probability of a galaxy being a radio source is much higher if the galaxy is a cluster member.

In the general area surveyed by Abell, there are 53 known extragalactic sources, of which 17 are in clusters, if clusters not listed by Abell, such as that of Cygnus A or that of 3C 295, are included. On the average, about one in ten galaxies is found to reside in a cluster. Thus, if the probability for a galaxy being a radio source were the same for galaxies within or without a cluster, the expectation would be that 5.3 of the sources, rather than 17, are in clusters.

This result can be verified more accurately by omitting those radio galaxies too faint to belong to an Abell cluster, and also omitting sources situated in low galactic latitudes, where the high obscuration makes it difficult to detect clusters. In this way, one finds 35 sources that could be in clusters listed by Abell. Of these, 14 are in Abell clusters, compared to the expectation of about 3.5. If thus the probability of a cluster galaxy being a source is relatively high, it seems quite plausible that a cluster may contain more than one source. There are indeed, in addition to the suspected cases mentioned, presently three sources identified with galaxies in the Virgo cluster, and two sources in the Perseus cluster.

It would be well to confine the discussion of the relation between radio sources and galaxies of the various types to galaxies brighter than the 17th magnitude. In this way, there is little error in determining galaxy types, although quite bright objects have been occasionally misclassified. Table II gives the results of this study for radio sources identified with galaxies above and below this 17th magnitude limit. Among the 30 bright galaxies there are 2 ellipticals, 1 Sa, 12 Sb, 14 Sc, 1 double spiral and two irregulars, so that a strong preference for spirals rather than ellipticals exists among them.

Table II

Magnitude	E, S0	Spiral	Double E	Peculiar
$m < 17$	22	2	8	6
$m > 17$	<—15—>		5	—

Apparently, no elliptical or peculiar galaxies identified with radio sources have absolute radio magnitudes fainter than $M_r = -22$, and no spirals are brighter than $M_r = -22$. Thus the spirals are, at most, weak sources.

DISCUSSION

Matthews: There are only about five sources identified with objects that are not very close to the radio positions. At least some of the elliptical galaxies which have been identified with radio sources are abnormal in the sense that they have very extensive envelopes. Morgan has found that objects of this type are present in about half of all clusters, and are always much brighter than the next brightest galaxy in the cluster. When a radio source identification exists in a cluster containing one of these objects, it is invariably the extended elliptical.

Minkowski: Yes, this property of elliptical radio galaxies is well known as, for example, in the case of NGC 6166. One might naively expect that being very extensive, these objects would have low velocity dispersions, but, in fact, the contrary has been found for M 87, NGC 6166 and 3C 40. These systems are all highly luminous optically, with absolute magnitudes of −21 or greater. It is certainly true that strong radio sources tend to be very luminous galaxies, but of course there are selection effects involved.

Optical Properties of Radio Galaxies

E. M. Burbidge
UNIVERSITY OF CALIFORNIA
SAN DIEGO

This paper is concerned with the optical characteristics of a number of the extragalactic radio sources for which identifications have now been available for some time.

MESSIER 82

M 82 is an irregular galaxy in which the presence of dust is evident. A recent study by Lynds and Sandage (*1*) has revealed some interesting facts about the well known filamentary structure, which is essentially aligned along the minor axis of this object. Some time ago, N. U. Mayall, then at Lick Observatory, showed that the galaxy is rotating. The recent work can be summarized as follows: On exposures taken in the blue light, one sees the extensive dust lanes, which thread right through the whole galaxy. In yellow light, the filaments are perceptible if not obvious, whereas they show up very well in the red. With an H-alpha interference filter they are even more prominent, and finally, if one superimposes a negative taken in H-alpha and a positive taken with a plate-filter combination that effectively records yellow continuum only, then the filaments appear as the dominant feature of M 82. Using the Lick 120-inch telescope, Lynds took spectra with the slit aligned along the minor axis and measured them for radial velocities. The analysis of the data suggests that the material in the filaments has been shot out from the center of the galaxy, assuming that Lynds and Sandage have correctly chosen the near side of the galaxy (based on the appearance of the dust structure). Allowing for a rather large deprojection factor, the explosive velocity is estimated at about 1000 km/sec. Further, a linear velocity-distance relation was found, with the fastest material being furthest from the galaxy center, and Lynds and Sandage concluded that the explosion occurred 1.5×10^6 years ago.

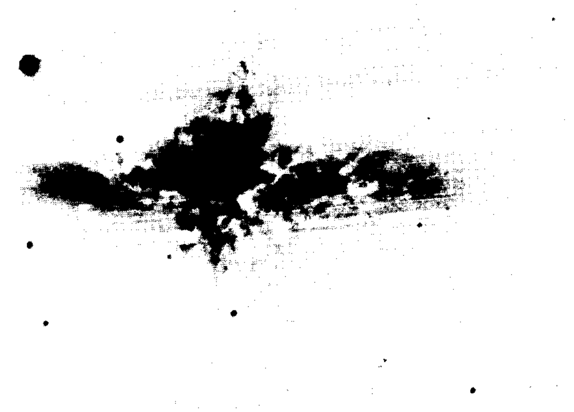


Figure 1—Messier 82: Hα interference filter photograph taken with 200-inch telescope, Mt. Palomar (negative print).

Besides H-alpha, the filaments appear to be emitting optical synchrotron radiation. This fact, together with the rather flat radio spectrum of M 82, reminds one of the Crab Nebula observations.

NGC 1068

NGC 1068 is a weak member of the class of strong radio emitters. It is one of the small group of spiral galaxies which C. K. Seyfert described many years ago (*2*). They are characterized by very bright nuclei, whose spectra show strong, high-excitation, emission lines, some of which have very broad wings. On the Doppler widening interpretation, these lines indicate velocities of up to 5×10^3 km/sec. A very faint luminous ring, which may be either gaseous or stellar, surrounds NGC 1068.

Some years ago, we measured (*3*) the rotation of this object and deduced the mass. The enormous velocity determined from the emission lines in the central region suggests that the gas is escaping from the system. More recently, M. F. Walker at Lick has taken spectra with the slit oriented along the line of maximum rotational velocity, as predicted from the earlier work. He finds that there is little symmetry between the two sides of the galaxy, indicating that the disordered motion persists well outside of the

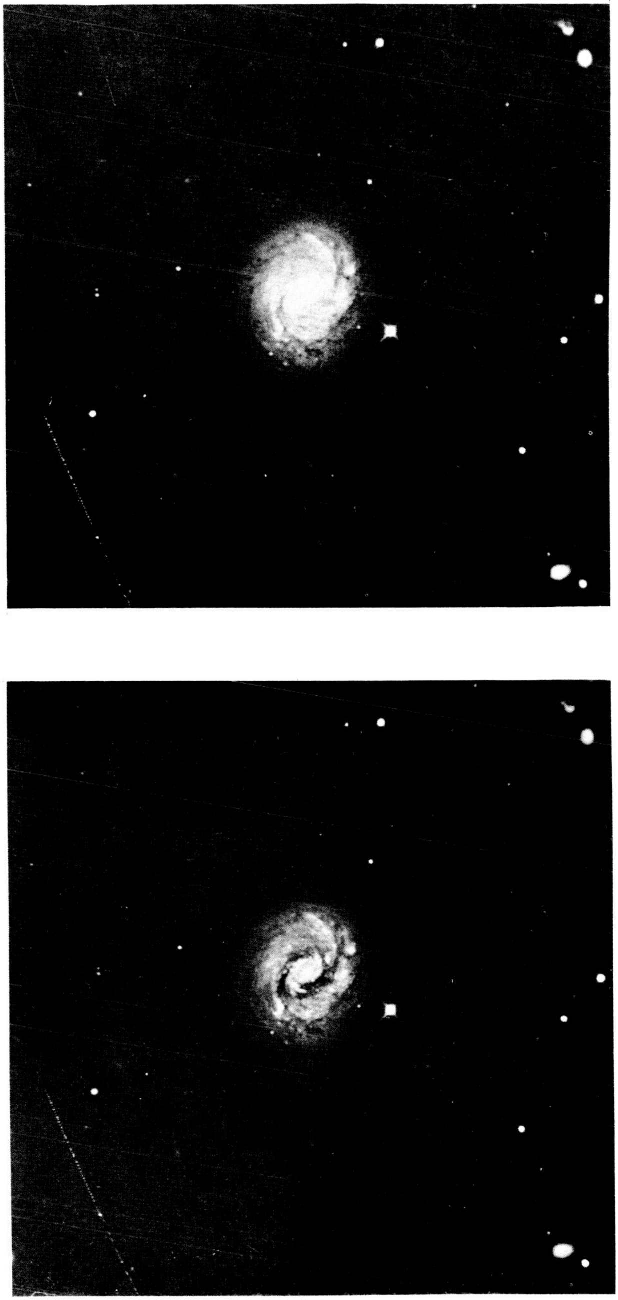


Figure 2—NGC 1068: (a) 82-inch telescope photograph (McDonald Observatory). (b) Print from same plate, "dodged" to show structure of bright central region.

nuclear region. Walker interprets the structure which one finds in the broad emission lines of the nuclear region as being due to the presence of discrete, randomly moving clouds; O. C. Wilson has observed similar phenomena in another Seyfert galaxy, NGC 4151 (unpublished).

NGC 7469

This Seyfert galaxy also has a faint outer ring of undetermined nature, and it has an irregular companion galaxy, IC 5283. NGC 7469 is known to be rotating (*4*) and its central region has very broad emission lines. It is roughly four times more distant than

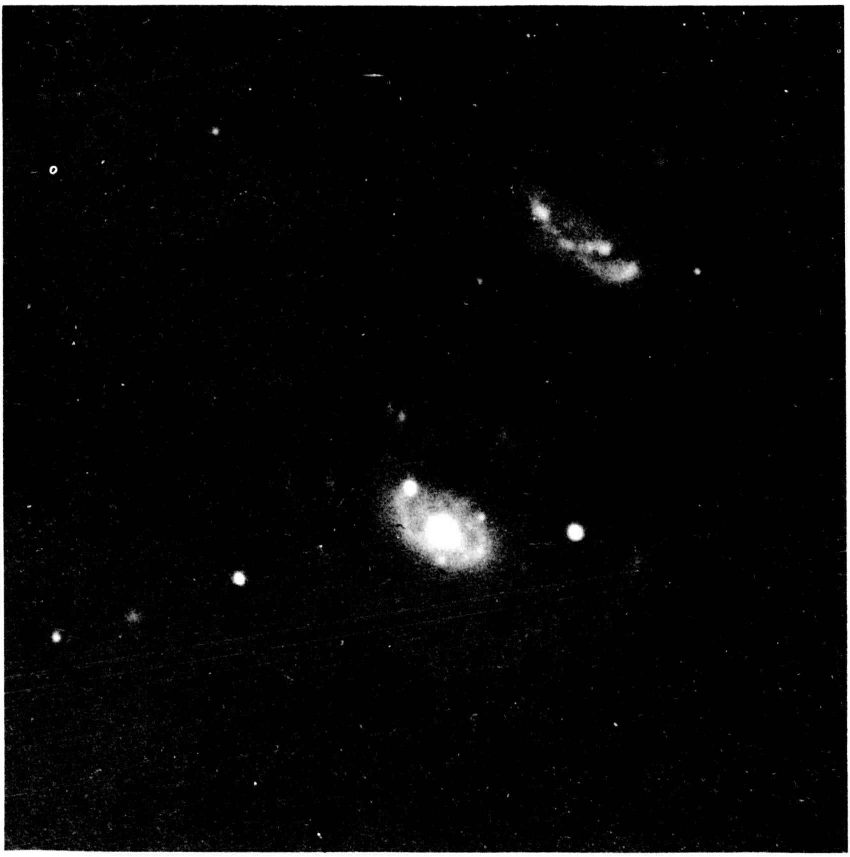


Figure 3—NGC 7469: Note bright nucleus and faint outer ring. IC 5283 is the irregular companion galaxy (Lick Observatory—120-inch telescope).

NGC 1068, so that it might be a radio emitter at the same power level without having been identified as one yet.

NGC 3226–27

Like NGC 7469, NGC 3226-27 is a double galaxy with the spiral, NGC 3227, exhibiting the Seyfert phenomenon. Again, a faint outer structure is present.

NGC 1275

NGC 1275 appeared in Seyfert's original list and has been identified as the chief source of radio emission in the Perseus cluster. Baade and Minkowski (5) suggested that it might be an example

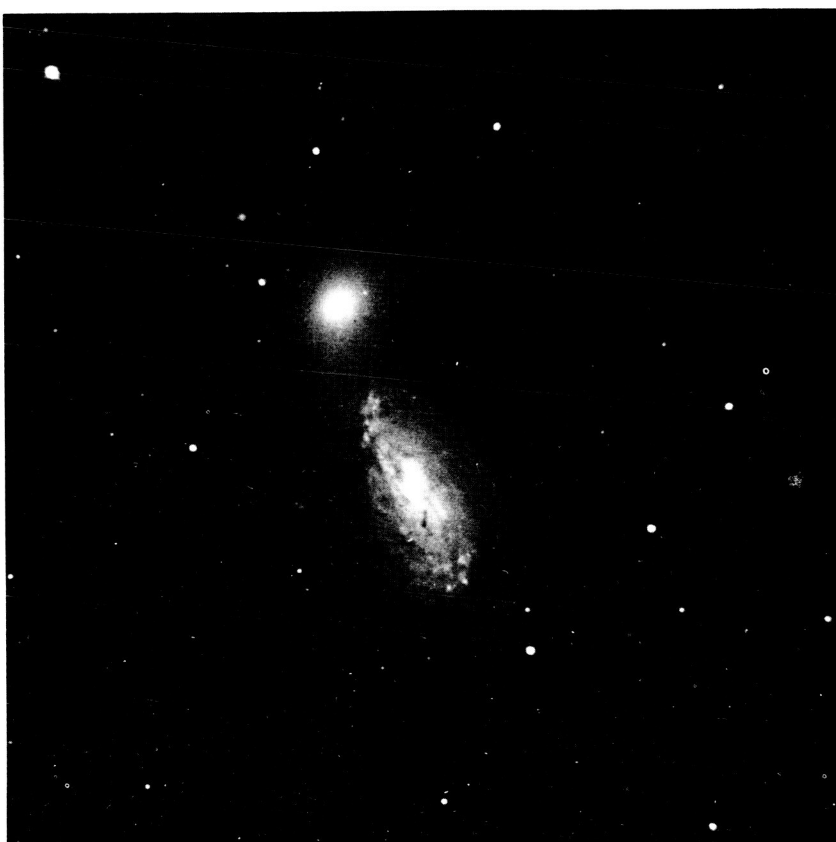


Figure 4—NGC 3226–27 (McDonald Observatory—82-inch telescope).

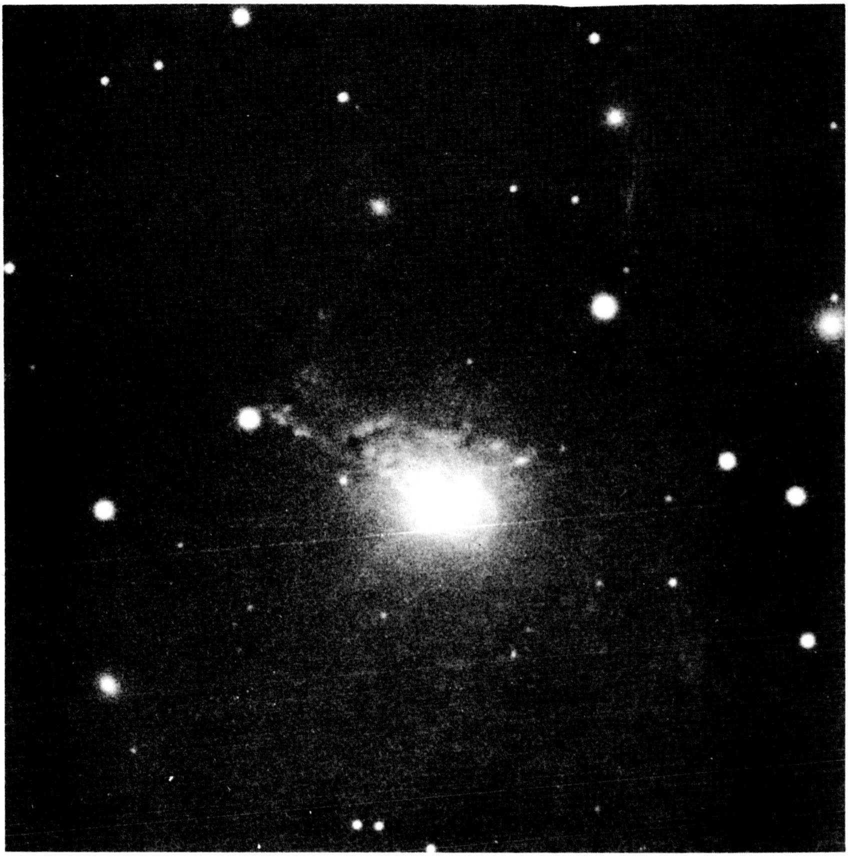


Figure 5—NGC 1275 (Lick Observatory—120-inch telescope).

of two galaxies in collision. This interpretation was based on the appearance of the object, as well as on radial velocity information. It looks more or less like an Sa or S0 galaxy, but on one side there is a large amount of gas and dust. The galaxy itself has a radial velocity in good agreement with the mean value for the Perseus cluster. However, the radial velocities of some of the patches of gas are greater by about 3000 km/sec than that pertaining to the galaxy. This made a very good case for collision; one ordinarily expects observed dust to be on the near side of the galaxy, and it was in the vicinity of the conspicuous dust patches of NGC 1275 that the large positive velocity difference was found. Thus, a galaxy may be coming from the near side of NGC 1275, passing through the bright component. The chief observational argument against this collisional model is that one does not see any nucleus associated with the supposed fainter galaxy.

Recent spectroscopic observations with the Lick 120-inch reflector have revealed that, besides the broad, Seyfert-type emission lines in NGC 1275, there is a narrow emission component, showing a considerable velocity difference from one side of the galaxy to the other, and located just outside the nucleus. This reminds one of the gas ejected from M 82; perhaps a similar phenomenon is taking place here.

NGC 5128

The most striking aspect of NGC 5128 is the well known dust lane, the great breadth of which suggests a high degree of turbulence. Spectra taken with the 82-inch McDonald telescope showed that there was a considerable velocity difference between the gas on one side of the nucleus and the gas on the other side. We inter-

Figure 6—NGC 5128 (McDonald Observatory—82-inch telescope).

preted this (*6*) as being due to rotation. A rough estimate of the mass yields about 2×10^{11} solar masses, so that this is a very massive system. There appears to be a difference of about 200 km/sec between the mean radial velocities of the gaseous and stellar components, in the sense that the gas is receding, but this result has rather low weight. A plot of radial velocities measured at various points in a line across the galaxy shows local "disturbances" of order 100-200 km/sec.

NGC 1316

The dust pattern in this galaxy is reminiscent of that in NGC 1275. There is a statement in the literature that NGC 1316 has no emission lines, but this is untrue. In fact, Lick and McDonald spectra have shown that there is an emission line in the red, which might be either H-alpha or λ 6583 of [N II]. If one assumes it to be λ 6583, which is often the stronger of these two lines in the nuclei of E, S0, Sa and some Sb galaxies, then one gets good agreement with the radial velocity given by Humason, Mayall and Sandage (*7*).

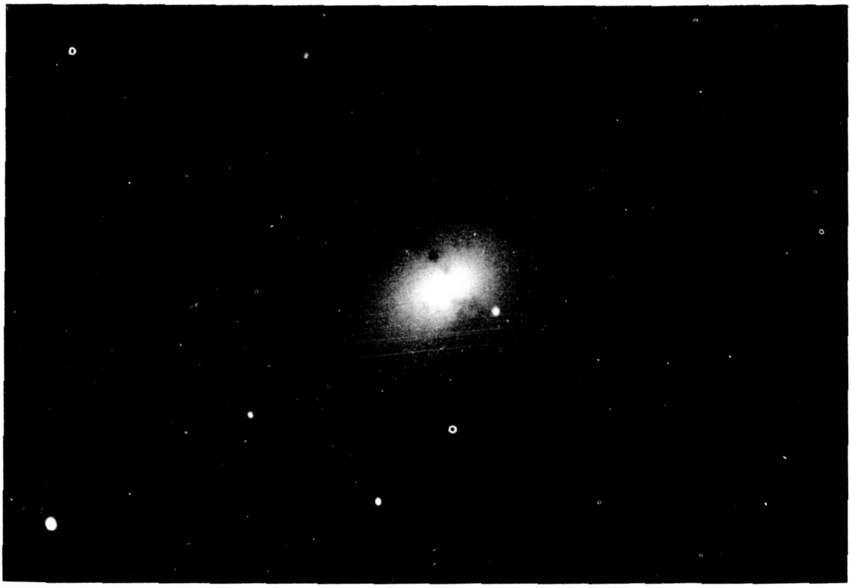


Figure 7—NGC 1316 (McDonald Observatory—82-inch telescope).

NGC 6166

This is a multiple elliptical galaxy, located in the cluster Abell 2199, which has been discussed by Minkowski (*8*), (*9*) and by the author (*10*). It has four components, one of which (A) is very extensive and has an intensity distribution which differs from those of the other three galaxies; also it has a very small nuclear region in which λ 3727 [O II] is emitted. Further, this largest component has a lack of symmetry which can be interpreted as being due to the presence of a dust bay, that is, a large absorbing cloud. Minkowski was able to obtain radial velocities for three of the components and found a large dispersion among them.

NGC 4782–83

This is a close pair of elliptical galaxies which show no emission lines in their spectra. Page (*11*) found a velocity difference of 630 km/sec between the two components, and Greenstein (*12*) confirmed this, obtaining a value of 670 km/sec. Assuming that the system was bound, Greenstein derived a minimum mass for each of the galaxies of 5.6×10^{11} solar masses; a more probable value is $\sim 10^{12}$ solar masses. Thus, if bound, this is a very massive system. The most striking feature optically in this system is the lack of symmetry in the outer isophotes of both galaxies. In a close double one might expect departures from spherical symmetry to occur along the line joining their centers, but here the chief asymmetry occurs in a direction nearly perpendicular to this. One does not know which of the pair is the radio emitter, but as NGC 4783 is the less centrally concentrated member, it is tempting to make a comparison with the NGC 6166 system, in which it appears that the large component with the least central concentration is the radio source.

NGC 750–51

This pair of EO galaxies is offered here as an example of a double galaxy which is not a radio source, so far as we know. A small degree of asymmetry can be noted in the light distribution but this is chiefly along the line joining the centers. I would like to emphasize, however, that we don't really know how frequently the light distributions in ellipticals differ from the Hubble law.

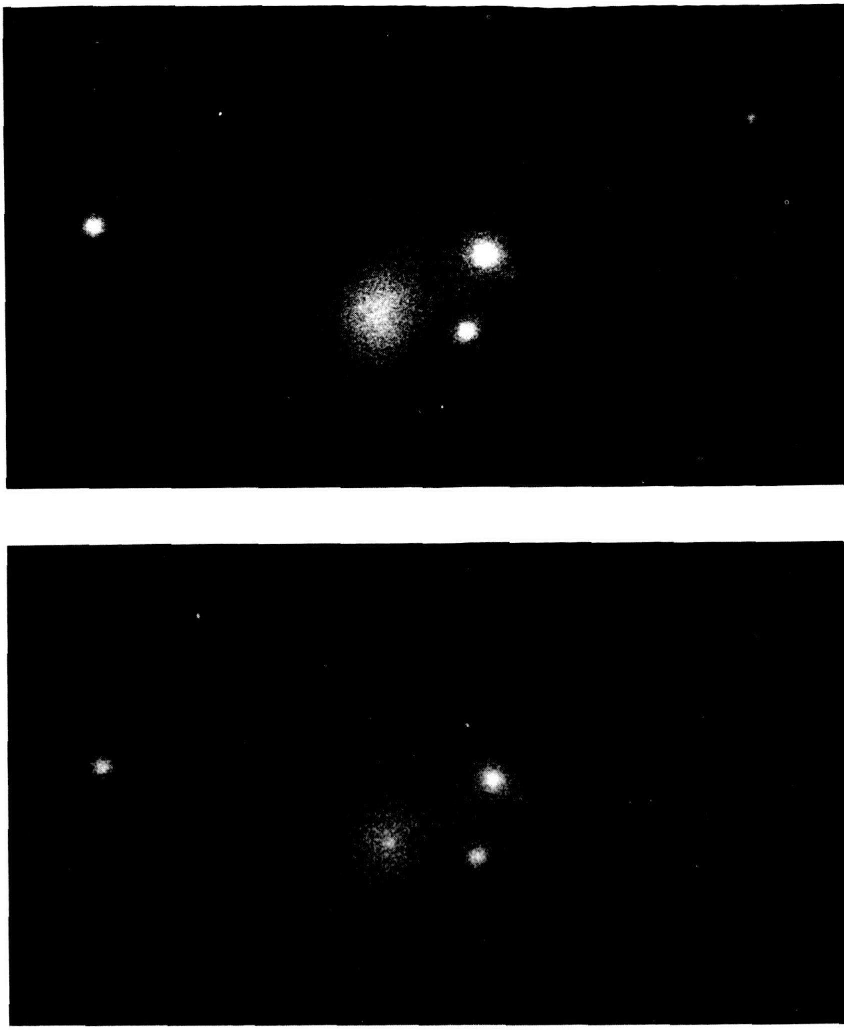


Figure 8—NGC 6166 (Lick Observatory—120-inch telescope). (a) Note dark feature on side of largest galaxy (component A). (b) λ 3727 emission of [O II] is responsible for much of light from nucleus of component A in this ultraviolet plate, taken with a fairly narrow bandpass.

MESSIER 87

Baade (*13*) discovered that the optical radiation from the famous "jet" of this galaxy was polarized. Osterbrock (*14*) found that the velocity profile of the λ 3727 emission line due to [O II] in the nuclear region (not the jet) of M 87 had a secondary

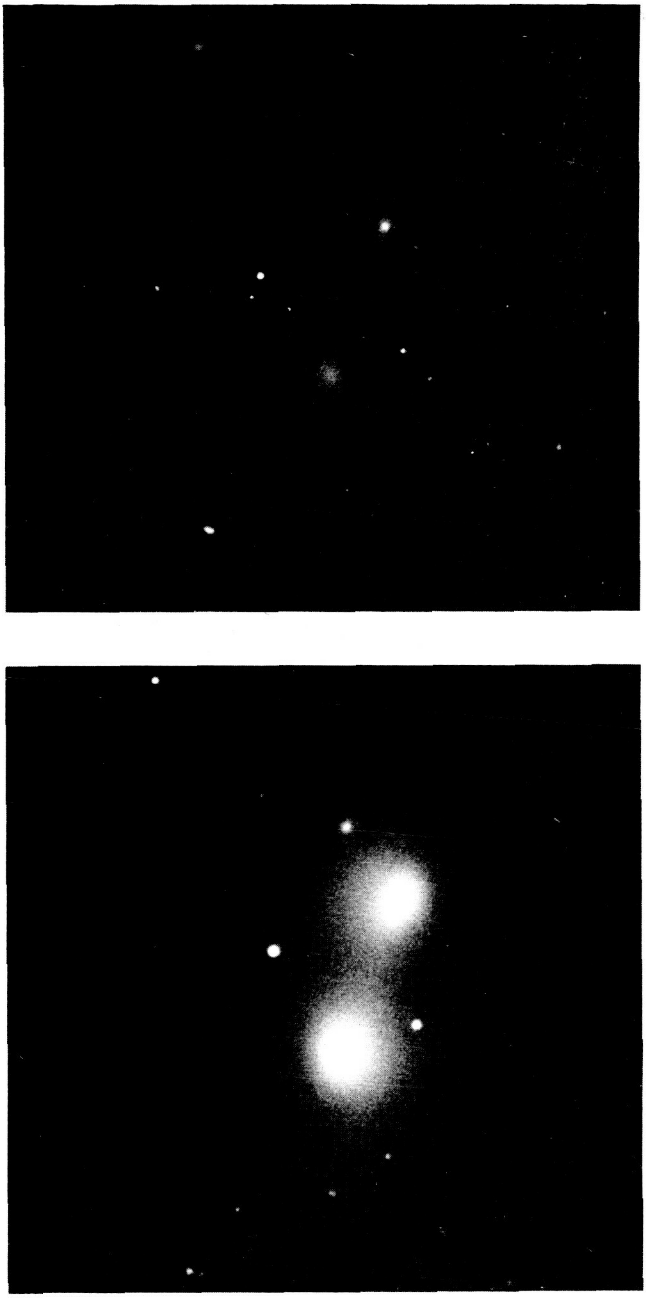


Figure 9—NGC 4782–83 (Lick Observatory—120-inch telescope).
(a) Nuclear regions—2-minute exposure.
(b) 45-minute exposure.

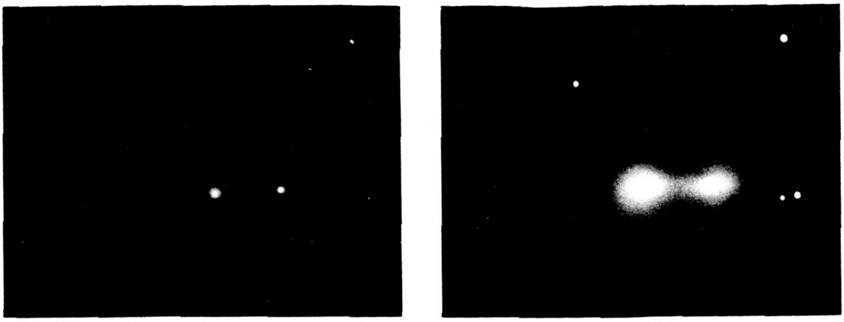


Figure 10—NGC 750–51 (Lick Observatory—120-inch telescope).
(a) Nuclear regions—5-minute exposure.
(b) 45-minute exposure.

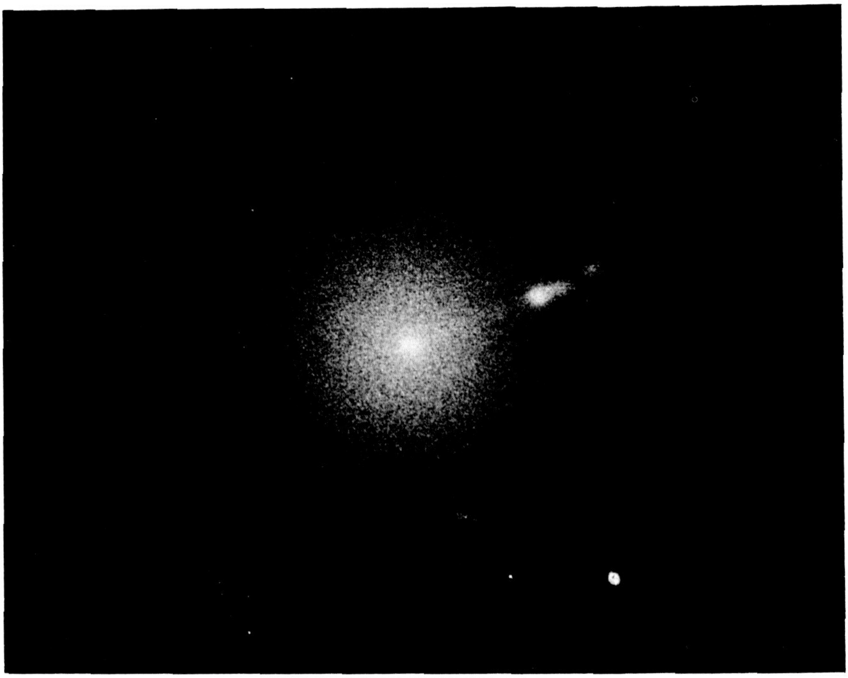


Figure 11—Messier 87. Central region showing the "jet" (Mt. Wilson and Palomar Observatories—200-inch telescope).

peak displaced 900 km/sec to the blue from the main peak which corresponds to the mean velocity of the galaxy. Thus, the gas has a component which is moving outwards from the center of the system.

3C 66

This elliptical galaxy also has a jet. Perhaps other, more distant ellipticals have similar features, too small and faint to be detected with present equipment.

3C 295

This radio source is identified with the brightest member of a distant cluster of galaxies.

3C 310

This pair of galaxies has a common envelope.

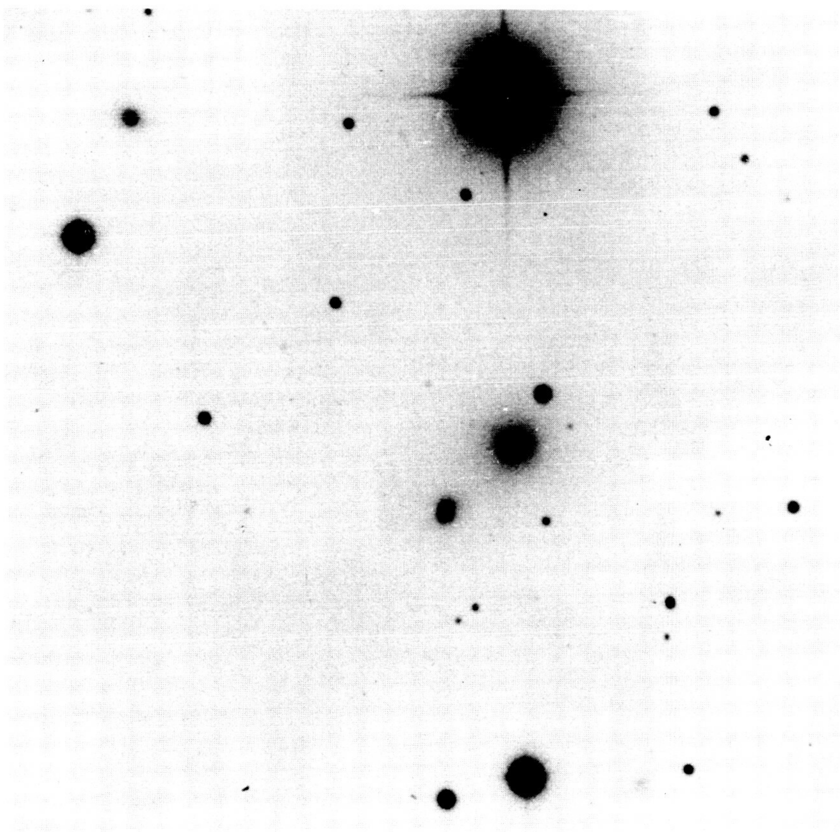


Figure 12—Galaxy associated with radio source 3C 66—negative print (Mt. Wilson and Palomar Observatories—200-inch telescope).

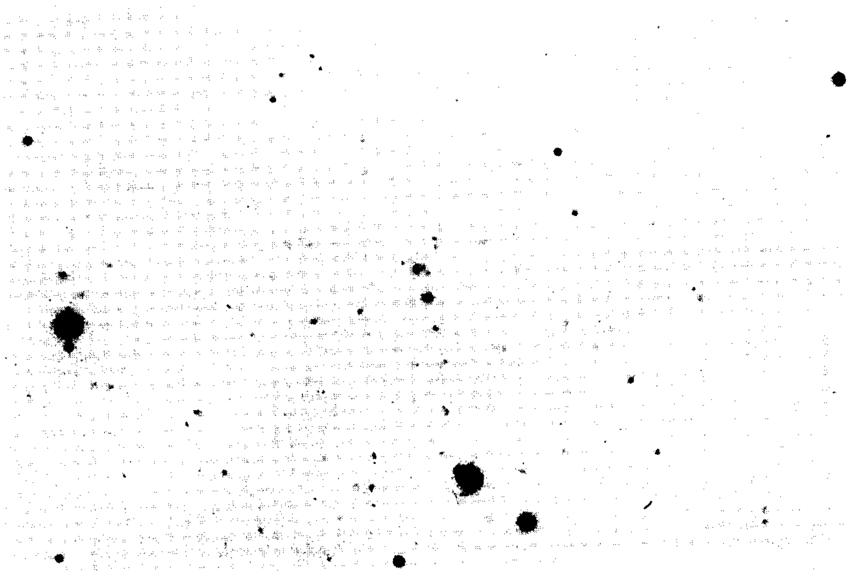


Figure 13—Red plate of a distant cluster of galaxies—negative print. 3C 295 has been identified with the brightest member (Mt. Wilson and Palomar Observatories—200-inch telescope).

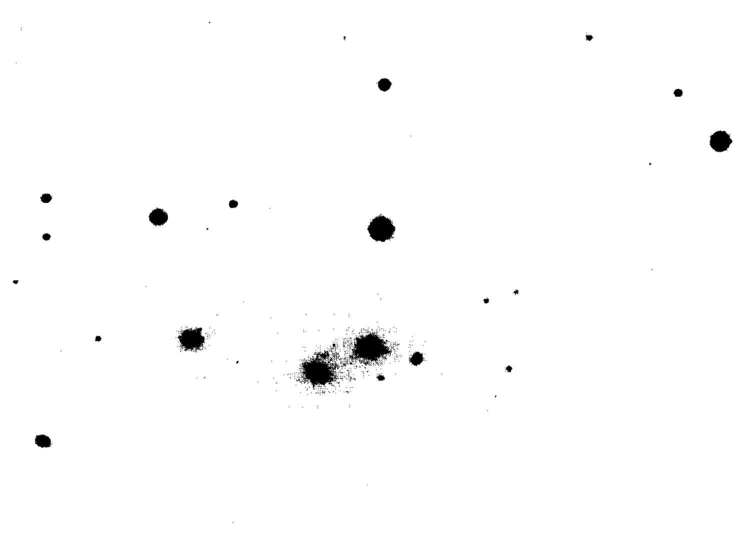


Figure 14—Double galaxy identified with 3C 310—negative print (Mt. Wilson and Palomar Observatories—200-inch telescope).

NGC 1218

Little is known about this object in the Perseus cluster. It is identified with the source 3C 78.

DISCUSSION

Radhakrishnan: 3C 66 is a widely spaced double source; the major axis runs roughly East-West. With the source resolved, we found an apparent polarization of about 3 per cent at λ 21 cm. If the polarized radiation comes from a small region, then it corresponds to about 1 per cent of the total intensity of the source.

Minkowski: There is another galaxy which may be associated with the source 3C 66.

Matthews: NGC 4151 is probably a weak radio source.

E. M. Burbidge: That is very interesting. O. C. Wilson found large random motions corresponding to discrete clouds in the central region of that galaxy.

Minkowski: How strong is the emission line in NGC 1316? What about the second [N II] line?

E. M. Burbidge: It is not very strong. There is a considerable amount of dust in the center, which may be absorbing the λ 3727 line, which you might expect to be as strong as λ 6583. As to detecting only the stronger [N II] line, it is frequently the case in these S0, Sa and Sb galaxies that λ 6583 is just intense enough to show up against the continuous background, with the weaker line, λ 6548, not being seen.

van der Laan: Is the jet in 3C 66 polarized like that in Messier 87?

Minkowski: I tried to get polarization exposures, but the 3C 66 jet is so evasive a feature that no conclusive result was obtained. At any rate, it does not seem to be strongly polarized.

REFERENCES

(*1*) Lynds, C. R. and A. R. Sandage (1963), Ap. J. *137*, 1005.
(*2*) Seyfert, C. K. (1943), Ap. J. *97*, 28.
(*3*) Burbidge, E. M., G. R. Burbidge and K. H. Prendergast (1959), Ap. J. *130*, 26.
(*4*) Burbidge, E. M., G. R. Burbidge and K. H. Prendergast (1963), Ap. J. *137*, 1022.
(*5*) Baade, W. and R. Minkowski (1954), Ap. J. *119*, 215.
(*6*) Burbidge, E. M. and G. R. Burbidge (1959), Ap. J. *129*, 271.
(*7*) Humason, M. L., N. U. Mayall and A. R. Sandage (1956), A. J. *61*, 97.
(*8*) Minkowski, R. (1958), P.A.S.P. *70*, 143.
(*9*) ———— (1961), A. J. *66*, 558.
(*10*) Burbidge, E. M. (1962), Ap. J. *136*, 1134.
(*11*) Page, T. (1952), Ap. J. *116*, 63.
(*12*) Greenstein, J. L. (1961), Ap. J. *133*, 335.
(*13*) Baade, W. (1956), Ap. J. *123*, 550.
(*14*) Osterbrock, D. E. (1960), Ap. J. *132*, 325.

Optical Spectra of Radio Galaxies

M. Schmidt
MT. WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Slit spectra are presently available for some 45 galaxies which have been identified with radio sources. One finds, on the basis of the emission lines, that these spectra can be divided into three classes, as follows:

a) spectra which lack emission lines;
b) spectra in which λ 3727 is the only bright line present;
c) spectra in which other emission lines, as well as λ 3727, occur.

Table 1 summarizes the distribution of radio galaxies in these three classes, on the basis of previous work as well as the present study, for which the plates were obtained at Mt. Palomar.

Table 1

Type of Emission Spectrum	No. of Galaxies	
	(previous work)	*(present study*)*
No emission	7	4
λ 3727 only	5	7
λ 3727 and others	5	17
All types	17	28

* Only galaxies not included in the "previous work" column are tabulated here.

Note (Table 1) that the more recently observed galaxies tend to have more emission lines recorded. This circumstance is presumably related to the fact that the author has restricted his own work to galaxies fainter than the 15th magnitude (optically), and therefore the average *radio* luminosity of the "present study" sample is brighter than that of the objects observed previously.

Redshifts have been measured for all but four of the galaxies considered above. Table 2 lists the frequency distribution of the parameter

$$z = \frac{\Delta\lambda}{\lambda}.$$

Table 2

z	No. of Galaxies	
	(previous work)	*(present study)*
.00–.05	12	7
.05–.10	2	10
.10–.15	0	3
.15–.20	1	3
.20–.25	0	2
.46	1	0
Total	16	25

A major objective of this investigation has been the classification of the galaxy spectra in terms of line emission strength. Due to the range in redshifts among the objects considered, it was necessary to restrict the selection of lines examined for relative intensity to a limited range of rest frequencies. Table 3 lists these emission lines in the order of appearance (*i.e.:* the greater the strength of the emission spectrum, the further down the list is the faintest line seen). Note that λ 3969, H_γ and H_δ appear essentially as a group, that is if any of the three is present, so are the other two. Lines which have been observed in only a few of these galaxies are listed in Table 4. λ 4471 is not observed.

In order to define an optical "emission strength," we chose six lines: $\lambda\lambda$ 3727, 5007, 4959, 3868, 3969, and H_β. The intensity of each of these lines, relative to the nearby continuum, was estimated for each galaxy. In this way it was possible to avoid the difficulties introduced by the change of emulsion sensitivity with wavelength and the differing redshifts of the galaxies studied. Of course, there is some uncertainty due to the fact that the various galaxies may well have different energy distributions in the con-

Table 3

λ 3727	[O II]
5007	[O III]
4959	[O III]
3868	[Ne III]
H_β	
3426	[Ne V]
3969	[Ne III]
H_γ	
H_δ	
4363	[O III]
4686	He II

Table 4

λ 3203	He II
3346	[Ne V]
H_ζ	
4026	He I
4070	[S II]
5200	[N I]

tinuum. The intensity of each line was measured on a scale of zero to six, with the latter figure indicating a very strong emission, and the sum of the intensity estimates for each galaxy was termed the emission strength, "S_6". Values of S_6 ranged from zero to 18; Cygnus A had the highest value.

Figure 1 shows the spectra of six galaxies, arranged in order of decreasing S_6. Note the extent of the emission along the slit and also the widths of the continua in the various spectra. The exposures were carefully guided, so as to assure that the position of the object on the slit remained constant. The lines are inclined in the spectrum of 3C 33, possibly indicating rotation. Just the weakest detectable emission at λ 3727 is found for the galaxy identified with 3C 310 (the lower spectrum of the pair at the bottom of Figure 1). If we accept this identification, then it is clear that the radio galaxy is more diffuse than its companion. However, in the case of 3C 315 the distribution along the slit is about the same for the two galaxies. The $\lambda\lambda$ 5577 and 6301 night sky lines, a Mercury line due to artificial light, and (in the case of Cygnus A) the foreground λ 3727 galactic emission are seen.

The spectra shown in Figure 1 are normal in the sense that the order in which the lines appear resembles that found for planetary nebulae and diffuse emission regions. However, we have observed two galaxies in which this rule fails: 3C 382 and MSH 23-1*12*. In

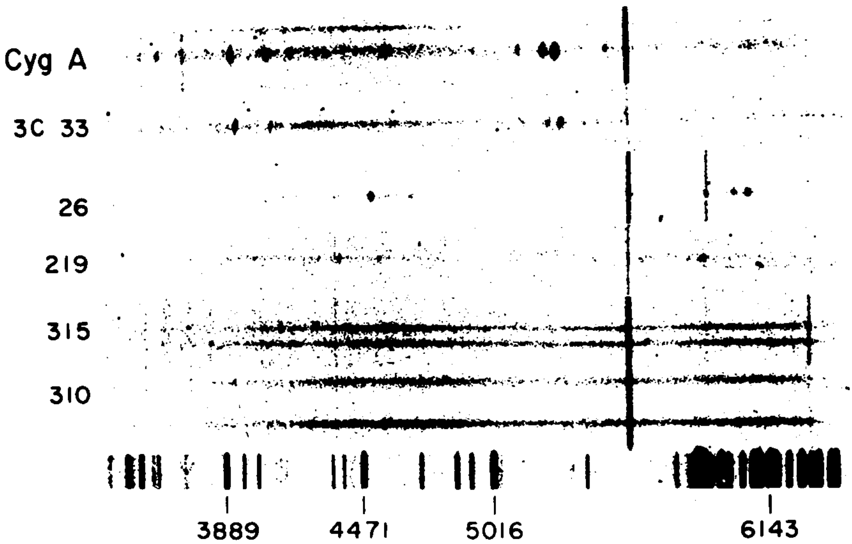


Figure 1—Optical spectra of six radio galaxies arranged in order of decreasing strength of the emission lines.

3C 382, the intensities of λλ 3426, 3868 and 3727 are all equal and also

$$H_\beta >> \lambda\ 4959.$$

MSH 23-1*12* shows extremely strong λ 3727, as well as λλ 4026, 4070, H_γ, H_β, and weak 5007 and 4959, but has no H_δ emission. The values of S_6 are given for several well-known sources in Table 5.

Table 5

Source	S_6
Cygnus A	18
Hercules A	2
3C 295	3:
Coma A	5
3C 353	2

There is a problem about how objects of large angular size, such as NGC 1068, should be classified. Looking at a published spectrum, one would give it one of the highest S_6 ratings. But if it were seen from a great distance, like the galaxies in Table 5, it is possible that none of the emission lines would be detected, because they are really limited to the nuclear region of the galaxy.

As far as the absorption spectrum is concerned, the H and K

lines of Ca II are generally observed when the continuum is sufficiently well-exposed. In some cases, one finds the *G* band, sodium lines, and the general system of iron absorption in the ultraviolet. In this respect, one is rather limited by the observations because in at least half of the spectrograms used the continuum is too weak. Nearly all of the objects studied are in the range of 15th to 20th magnitude.

Table 6 summarizes the sources whose absorption spectra appear to be abnormal. Excepting 3C 353, it appears from this rather small sample that the absorption lines are absent only if S_6 is 7 or greater. If this holds true, then about one-third of the sources lack absorption.

Table 6

Source	S_6	*Abnormality*
3C 198	7	No absorption
234	17	No absorption
353	2	No absorption
382	7	Very weak *K* ?
445	15	No absorption

Figure 2 consists of the spectra of five galaxies having high emission strengths (as summarized in Table 7), arranged vertically in order of the redshifts, which range from about 10,000 to

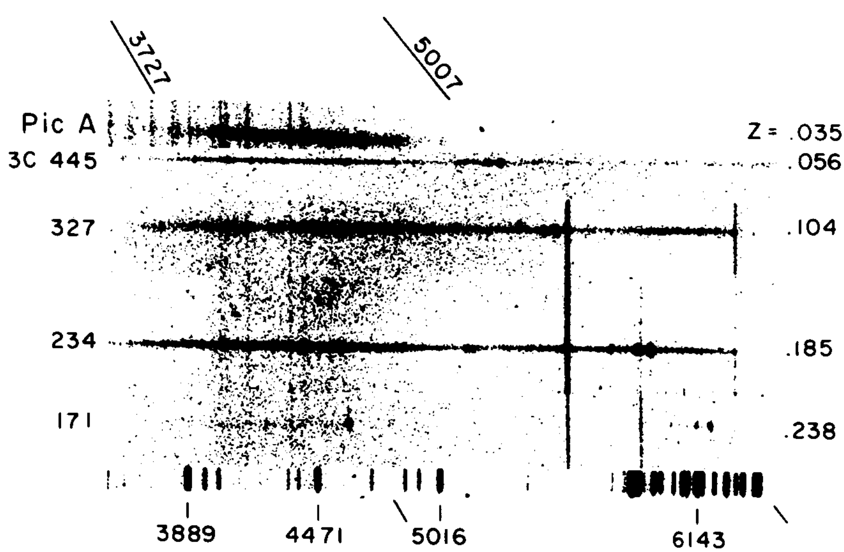


Figure 2—Optical spectra of five radio galaxies arranged in order of increasing redshift.

72,000 km/sec. The spectra are aligned horizontally so that the night sky emissions fall on vertical lines. The emission lines of the five galaxy spectra lie along inclined lines, which are indicated in the figure for $\lambda\lambda$ 3727 and 5007. In the case of Pictor A (which has an effective apparent magnitude of 18 due to its low altitude at Palomar), the spectrum is very wide due to the great difficulty in guiding, and is also inclined due to differential atmospheric refraction.

Table 7

Source	S_6
Pictor A	15:
3C 445	15
327	17
234	17
171	13

If the Balmer decrement were the same in all of these objects, one could get an indication of their relative temperatures from the ratio of the λ 4363 and H_γ intensities. In 3C 445,

$$\lambda\ 4363 > H_\gamma$$

so that the electron temperature is very high.

An attempt has been made to see if the emission strength S_6 is correlated with any of the other properties of the radio sources. The results, which are essentially negative, are as follows:

1. The correlation between S_6 and L_R, the radio luminosity discussed by Matthews, is at best extremely weak, in the sense that L_R increases with S_6. For $L_R < 10^{42}$ erg/sec, emission lines are not seen.

2. There is no correlation between S_6 and the radio size or radio character (*e.g.:* halo-core or double source).

3. There is no correlation, or only a weak one, between S_6 and the linear size of the optical emission (*i.e.:* length along the slit).

4. There is a correlation between the size of the optical emission and the redshift z, but that is exactly what is expected if one always makes the same guiding error in seconds of arc.

5. There is no correlation between S_6 and the spectral index α.

6. There is no correlation between S_6 and the occurrence of optical absorption features.

7. Comparison with the radio spectral classifications discussed by Conway suggests at most a weak correlation between high S_6 and radio spectra of types C and S-2.

The emission sizes discussed appear to be of the order of 1 to possibly 10 kiloparsecs.

DISCUSSION

Greenstein: There have been many cosmological controversies involving the radio sources and it is interesting that a wide variety of elements is present in them. We had hoped that when we obtained optical spectra for the radio sources, we would find some indication that they might be either much less or appreciably more than 10^9 years old. Unfortunately, it seems that, given the conventional theories of nucleosynthesis, all one can say is that these radio galaxies must have an age of a least 5×10^8 to 10^9 years, in order to account for the synthesis of the observed elements from an initial pure hydrogen composition.

Cameron: As little as 3×10^6 years might suffice for the production of most of the elements.

Greenstein: High dispersion spectrograms would permit a much more sensitive test than does the present observational material, because then we could search for elements which cannot be formed in less than 5×10^9 years, whether we believe Cameron's theory or that of Burbidge, Burbidge, Fowler and Hoyle.

G. Burbidge: I am inclined to compare these spectra with those of the Seyfert galaxies. Ions which have never been detected in the radio sources, such as Fe VII, are observed in the Seyfert objects.

E. M. Burbidge: Can the observations of peculiar line intensity ratios in some of the radio galaxies be explained on the supposition that regions of different temperature exist?

Schmidt: I am not sure. It would certainly be very valuable if electron temperatures could be determined by means of photoelectric scanner observations of the [O III] lines.

Matthews: There are three sources which might be of interest because they have emission spectra although in each case $L_R < 10^{42}$ ergs/sec. They are M 82, NGC 1068 and 1275.

Schmidt: I am uncertain as to how these objects should be classified. Perhaps, if they were seen at apparent magnitude 15 or fainter, we might see no more than weak λ 3727 emission.

G. Burbidge: In these objects, a significant fraction of the total light may come out in the emission lines. I have done some calculations based on data given by Seyfert for the photographic region. The result is that about 10^{42} ergs/sec are emitted in the lines. For M 82, based on the work of Lynds and Sandage, there are $\sim 10^{41}$ ergs/sec in H_α.

Quasi-Stellar Radio Sources*

Thomas A. Matthews
OWENS VALLEY RADIO OBSERVATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

REFERENCES

The major articles discussing the identification, properties and nature of the quasi-stellar radio sources are listed below.

Greenstein, J. L. and T. A. Matthews (1963), Nature *197,* 1041.
Hazard, C., M. B. Mackey and A. J. Shimmins (1963), Nature *197,* 1037.
Matthews, T. A., J. G. Bolton, J. L. Greenstein, G. Münch and A. R. Sandage (1961), Sky & Telescope *21,* 148 .
Matthews, T. A. and A. R. Sandage (1963), Ap. J. *138,* 30.
Schmidt, M. (1962), Ap. J. *136,* 684.

*In view of rapid developments in this field since the Conference on Physics of Nonthermal Radio Sources was held, we have omitted the contributions of several workers on quasi-stellar sources from this volume. The reader should consult the above references and especially also the forthcoming proceedings of the Dallas Symposium on Gravitational Collapse and Other Topics in Relativistic Astrophysics.— (*Editors*)

Theory

Mechanisms of Energy Generation in Extragalactic Radio Sources

G. R. Burbidge
UNIVERSITY OF CALIFORNIA
SAN DIEGO

N65 13263

1. OBSERVATIONS OF GREAT ENERGY RELEASES IN GALAXIES

Before reviewing the various theories which have been proposed to account for the origin of the great energies observed in the strong extragalactic radio sources, I would like to point out that these sources do not constitute the only instances of sudden, large-scale energy releases in galaxies. There is considerable circumstantial evidence which suggests that such phenomena are in fact fairly common.

The Seyfert galaxies, for example, seem to be the sites of very violent disturbances. About nine of these objects are known among the bright spiral galaxies. On direct photographs, their distinguishing characteristic is the presence of a small, extremely bright nucleus. Their spectra contain a large number of strong, broad emission lines, in which structural details can be resolved. These spectra are interpreted as revealing very large velocities for the gaseous matter in the nuclei of the Seyfert galaxies, and the presence of discrete components in the emission features can presumably be ascribed to the existence either of individual clouds having random velocities of several thousand kilometers per second, or of shock fronts moving through the gas, with Mach numbers in the range of ten to one hundred. Of course, hydromagnetic shocks should also be considered here, although we can only guess at the magnetic field strengths in the nuclei of galaxies. A few of the Seyfert galaxies are known radio emitters, such as NGC 1068 and 1275, and it is quite possible that the others will be detected as weak radio sources.

Minkowski's analysis of the optical spectrum of NGC 1275 led to the conclusion that a collision between two galaxies has occurred. However, there is general agreement nowadays that the collisional hypothesis must be discarded for radio sources in general, and so possibly the origin of the NGC 1275 radio emission is independent of whether this object is actually involved in a collision. On the other hand, the author believes that the emission lines observed to have a velocity of ~3000 km/sec with respect to the nucleus of this object should be ascribed not to another galaxy (as on the collision model) but rather to material which has been ejected from the central region of NGC 1275 and is moving outward at the observed velocity, with a characteristic distance of 20 kiloparsecs from the center.

Messier 82 is another type of system in which very violent processes seem to have taken place. It appears to be an irregular galaxy in which, according to the remarkable study by Sandage and Lynds, material has also been ejected from the central nucleus. Filaments of this gas have reached heights of several kiloparsecs above the plane of the galaxy and the presence of optical synchrotron radiation is suggested by the polarization measurements obtained by Elvius and Hall. Further, M 82 is a weak radio source. Sandage and Lynds derived an age of 1.5 million years for the filaments, but since they neglected the deceleration which may have occurred over this interval, it may be regarded as an upper limit. This argument assumed that the filaments were in fact ejected from the center; other models suggest that the quoted age may actually be a *lower* limit.

Virgo A represents a different type of system. The galaxy, Messier 87, is a very bright elliptical. The famous "jet", near the central region, has been detected both optically and on radio waves. Spectra show that gas in this system is expanding with a velocity of 900 km/sec in the line of sight. However, the mass of the galaxy, as derived by Minkowski from the velocity dispersion of member stars, is sufficiently great so that the expanding gas will probably not be able to escape from the system.

The optical spectrum of Cygnus A resembles that of a Seyfert galaxy in terms of the emission line strengths. The line widths, however, are much narrower in Cygnus A. In both Cygnus A and the Seyfert objects, 10^{42} ergs/sec is a typical value for the energy radiated in lines of the photographic region.

The author has calculated

$$10^{55\pm2} \text{ ergs}$$

as the kinetic energy residing in the gas observed at the nucleus of a Seyfert galaxy. The great breadth of the emission lines indicates that the gas must be escaping, unless one accepts the suggestion once made by Woltjer that the nuclei of these objects are exceedingly massive. For purposes of comparison, we may note that the observations of optical synchrotron radiation in Messier 82 and the Virgo A jet lead to a minimum energy of 10^{55} ergs for the high energy particles and magnetic flux in these objects.

2. THE RATIO OF ENERGIES STORED IN PROTONS AND ELECTRONS

One of the major problems in discussing the strong radio sources is that of determining the ratio

$$E_p/E_e$$

of the energies in protons and electrons, respectively. The observations of synchrotron radiation lead at most to estimates of E_e. Among the arguments which have been presented in this connection, we may note the following:

A) In most acceleration mechanisms at low energies, it appears that protons are less vulnerable to energy losses than electrons, if they begin with comparable energies.

B) In our Galaxy (for the present epoch, at least), we observe that $E_p/E_e = 100$ for the primary cosmic rays.

C) $E_p/E_e = 100$ turned out to be the appropriate value for a model of M 87 which the author calculated some years ago.

The M 87 model consisted of assuming first that the electrons and positrons are produced by secondary interactions following the collision of energetic protons with the ambient gas, and next that an equilibrium is reached in which the energy radiated by the synchrotron process is provided by that being continuously transferred from the proton flux to the electron flux. (Probably only some 5% of the initial kinetic energy gets out in synchrotron radiation, as much of it is radiated in gamma rays and neutrinos, and further one has to take account of the meson production and the efficiency with which energy is transferred to the electrons and positrons.)

It does not follow that the value $E_p/E_e = 100$ suggested for M 87 is appropriate for the stronger radio sources. Most of the theories which have been proposed assume that the primary energetic particles are produced in the nuclear region of the galaxy, and it does seem that the M 87 model requires this also. However, when the cloud expands into the halo region, the density is too low for the suggested mechanism to be very important. Secondary production becomes negligible, unless the protons are trapped indefinitely, and this seems very unlikely.

3. TIME SCALES OF EXTRAGALACTIC RADIO SOURCES

There are two ways of estimating time scales for the radio sources. The first is obtained by dividing a characteristic dimension of the source by an appropriate velocity. For example, the velocity with which the high velocity gas escapes is pertinent for a Seyfert galaxy. In such a case, the relatively small volume of the source and the velocity of $\sim 10^3$ km/sec lead to short time scales, say $\sim 10^4$ years. In the strong radio sources, if the particles are moving outward with velocity near that of light, the dimensions give time scales $\sim 10^5 - 10^6$ years. The second time scale is that associated with the half-life of electrons of given energy, which are radiating by the synchrotron mechanism. The observational datum usually discussed in this connection is the presence (or non-presence) of a high-frequency cutoff in the radio spectrum.

The most recent indications are that the time scales associated with the extragalactic radio sources are all of the order of 10^6 years or less, that is, very small compared to the age of a galaxy. As one would expect, even shorter ages are associated with the optical synchrotron sources. For example, in the Crab Nebula (a galactic source), the time scale for the electrons seems to be 10^2 years, and in M 82 and the M 87 jet, the corresponding values are 10^3 to 10^4 years. The Sandage and Lynds figure of 1.5×10^6 years for the filaments in M 82 therefore suggests that many generations of electrons have been produced, if the optical synchrotron radiation has always been present. It is helpful here to invoke the model in which the radiating electrons are secondaries produced by the collision of a flux of protons with the ambient gas; otherwise we have to imagine that a number of discrete events has occurred to give rise to the relativistic electrons.

4. MAGNETIC FIELDS AND THE ENERGY IN PARTICLES

Earlier in the conference, Dr. Matthews presented some computations (Table 1), which were calculated on the assumption that

$$E_p = 100\, E_e.$$

From this data, one sees that in general fields of 10^{-5} gauss or greater are required, a notable exception being 5×10^{-4} gauss for Cygnus A. Some computations which the author made along the same lines a few years ago are shown in Table 2. Two alternate sets of the minimum values of the total energy are presented for

TABLE 1

REQUIRED MAGNETIC FIELD STRENGTHS AND ENERGIES FOR SEVERAL SOURCES

(After Matthews.)

Source	log L (erg/sec)	log V (pc^3)	H (gamma)	log E (erg)
Cyg A	44.64	12.20	50	59.9
3C 295	44.64	11.70	50	59.3
Her A	44.04	15.03	5	60.7
3C 219	43.34	15.36	2	60.3
3C 33	42.60	$\leqslant$ 11.53	$\geqslant$ 10	$\leqslant$ 58.5
3C 353	42.34	13.23	4	58.8
3C 198	42.20	15.91	0.8	60.0
3C 78	41.84	13.10	3	58.5
3C 338	41.70	13.23	4	58.7
Vir A core	41.20	8.93	30	56.3
Vir A halo	41.11	12.68	3	58.0
For A	41.46	14.87	0.8	59.0
Cen A core	40.68	10.64	8	56.8
Cen A halo	41.20	15.26	0.6	59.3
3C 278	41.15	13.06	2	58.3
3C 270	40.36	11.83	3	57.3
3C 71	39.87	8.04	20	55.0

TABLE 2

MINIMUM ENERGIES REQUIRED FOR SYNCHROTRON EMISSION IN GALAXIES

	Rate of Emission (ergs/sec)	Total Energy (Electrons + Mag. Energy) (ergs)	Mean Value of H (gauss)	Total Energy (Protons + Mag. Energy) (ergs)	Mean Value of H (gauss)
Galaxy*	$\sim 10^{38}$	$\sim 3 \times 10^{54}$ (electrons) $\sim 10^{56}$ (mag. field)	....	$\sim 3 \times 10^{56}$	7×10^{-6} (disk) 2×10^{-6} (halo)
M31†	1.9×10^{38}	2.1×10^{55}	8×10^{-7}	3.0×10^{56}	3×10^{-6}
Magellanic Clouds	1.3×10^{37}	2.5×10^{54}	1×10^{-6}	3.4×10^{55}	4×10^{-6}
NGC 4038-39	2.1×10^{39}	1.7×10^{56}	2×10^{-6}	2.3×10^{57}	7×10^{-6}
NGC 1068	7.5×10^{39}	3.2×10^{55}	2×10^{-5}	3.6×10^{56}	6×10^{-5}
NGC 5128 (central region)	2.4×10^{41}	3.2×10^{56}	2×10^{-5}	4.4×10^{57}	9×10^{-5}
NGC 5128 (halo)†	2.2×10^{41}	5.0×10^{58}	1×10^{-6}	7.0×10^{59}	5×10^{-6}
NGC 1316 (central region)	8×10^{40}	2.1×10^{56}	2×10^{-5}	3.0×10^{57}	6×10^{-5}
NGC 1316 (halo)†	1.6×10^{41}	1.8×10^{58}	1×10^{-6}	3.2×10^{59}	5×10^{-6}
NGC 4486 (jet)	2.3×10^{42}	1.7×10^{54}	2×10^{-4}	2.4×10^{55}	7×10^{-4}
NGC 4486 (central radio source)	3.5×10^{41}	1.7×10^{57}	1×10^{-5}	2.4×10^{58}	4×10^{-5}
NGC 1275	6.4×10^{41}	9.4×10^{56}	2×10^{-5}	1.3×10^{58}	8×10^{-5}
NGC 6166	7.8×10^{42}	1.4×10^{57}	3×10^{-5}	1.9×10^{58}	1×10^{-4}
Hydra A	1.5×10^{43}	1.0×10^{58}	8×10^{-5}	1.5×10^{59}	3×10^{-4}
Cygnus A†	5.7×10^{44}	2.8×10^{59}	4×10^{-5}	3.9×10^{60}	2×10^{-4}
Coma Cluster	1.0×10^{41}	2.9×10^{59}	2×10^{-7}	4.0×10^{60}	7×10^{-6}

*Energies derived by means other than that of using the minimum total energy argument.
†For sources marked with this symbol, radio diameters were used.

various sources; in the first set the total particle energy is taken as twice the electron-positron energy, whereas in the second we again took E_p/E_e as 100.

It seems unreasonable to suppose that fields of several gammas or more are present in these very large volumes where the densities are very low. The alternative is that the particle energy of a source must be much greater than the values shown in Tables 1 and 2, which were computed on the assumption that the total particle and magnetic energies are equal.

5. CONSEQUENCES OF SHORT TIME SCALES

If the total particle energy in a source is much greater than the magnetic energy, then the particles must just burst out of the system, radiating in the observed large volumes, and this fast escape means that the time scale is very short. It follows from these short source lifetimes and the observed ratio of sources to galaxies that the frequency with which galaxies become radio emitters is much greater than was originally believed. At present one cannot actually determine this frequency because it is not known whether some types of galaxies are more likely to become sources than others, or if a given galaxy can repeatedly become a source or whether, for example, different types of galaxies become radio sources of different strengths. It also follows from this model that the bulk of the energy does not go into radio emission but rather escapes in the form of high energy particles, and thus we have a very efficient mechanism for the production of cosmic rays.

If one takes the Virgo cluster of galaxies and assumes that sources have been present there continuously in numbers equivalent to that observed at the present time, then it is possible to show that an appreciable cosmic ray density has resulted, in fact, one which is perhaps comparable to the cosmic ray energy density in our Galaxy.

6. MECHANISMS OF ENERGY GENERATION

In this section an attempt is made to summarize some of the proposals which have been put forward to account for the great total particle energies which must be present in the strong radio sources.

The situation in this field today is very much like that which existed in stellar astrophysics some forty years ago, when it was well known that an energy source other than gravitational energy had to be present in the stars, but no one knew just what it was. Only one real result was available, namely the equivalence of mass and energy which was shown by Einstein. One school of astronomers believed that radioactivity was responsible, another that the energy was released by annihilation of protons and electrons, and so on.

We can divide the various theories for the energy source of strong radio galaxies into two classes, depending on whether or not the energy which is released originates within the galaxy in question. Among the schemes in which the energy is released from sources which were originally external to the galaxy are:

(1) The collisional hypothesis of Baade and Minkowski;

(2) Shklovsky's recent model for Virgo A, in which gas, amounting to about 10 solar masses per year, flows into the system, is accelerated, and is then ejected in the form of plasma clouds which supply energy to the jet. Thus the gravitational energy is released as material falls in. He interprets the λ 3727 emission line, which has a radial velocity of 10^3 km/sec relative to the center of M 87, as indicating that there is a continuous outflow of gas in the jet.

(3) The suggestion by the author, which has been elaborated upon by Hoyle and himself, that the required energy source may be the annihilation of matter and anti-matter. This idea has the virtue that electrons, but no protons, are produced. However, there are a number of serious disadvantages, including the fact that an additional process is required, since the electrons are not highly energetic when created, but need to be accelerated up to as much as 100 Bev, for the optical synchrotron emitters.

The theories in which the energy production is internal to the source galaxies include the following:

(1) Shklovsky's proposal, made several years ago, that the supernova occurence rate, again for Virgo A, is very high.

(2) The conjecture of Ambartsumian that energy is released in some way from interstellar matter.

(3) The hypothesis of collective stellar formation, discussed in this volume by Cameron, which is essentially related to suggestion (1). The author has previously described his reasons for doubting that this mechanism can operate, especially for the central regions of elliptical galaxies.

(4) The "galactic flare" theory of Hoyle, which is similar to the solar flare model of Gold and himself. The argument is that, given the large amount of dust and angular momentum in the nuclear region of a galaxy, one expects the magnetic field to be twisted up, and eventually a discharge mechanism becomes operative as the material

is squeezed together. A large particle flux is produced by the discharge. The particle energy thus comes from the magnetic energy, which essentially comes itself from the rotational energy of the system, assuming that the field was amplified by the twisting process.

(5) The author's "detonation wave" theory, in which one supernova, exploding in a densely populated galactic nucleus as a consequence of normal evolutionary processes, triggers nearby stars into similar explosions. We should note that it has not yet actually been demonstrated that the detonation wave will in fact propagate into the interiors of stars. A very high density of stars is required, and this cannot be ruled out observationally.

(6) The recent discussion by Hoyle and Fowler of the evolution of a star of 10^5 to 10^8 solar masses (depending on the type of galaxy). Here it is argued that the release of gravitational energy in the ultimate collapse of the object is able to explain the strongest sources.

7. A COMMENT ON THE ORIGIN OF DOUBLE SOURCES

We frequently observe radio sources which consist of two emitting regions centered about the optical galaxy. These distributions must be related to the initial configuration in which the outburst occurred. Assuming that an originally spherically symmetrical outburst took place in a galaxy in which the ambient gas was confined to a plane, then clearly the result will not be a spherical source, since the ejected material can move most easily at right angles to the plane. In the case of NGC 5128, the radio brightness distribution suggests that more than one such event has occurred.

DISCUSSION

Moffet: In the double source 3C 33, the two components have E-W diameters of less than 10 kiloparsecs but are separated, nearly in the N-S direction, by over 200 kiloparsecs. On the weak field models discussed here, it seems remarkable that these components could have remained so compact if they were blown out from the central region.

Woltjer: Taking your time scale of 10^4 years for the Seyfert phenomenon and remembering that about 1% of all galaxies brighter than 14th magnitude are Seyfert systems, would you then conclude that a normal galaxy becomes a Seyfert galaxy 10,000 times during its lifetime?

G. R. Burbidge: Yes, I think one is driven to the argument that these events occur frequently.

Maran: Is is possible to determine how frequently Seyfert galaxies are observed to occur in a cluster of galaxies?

Minkowski: The statistical sample is too small.

Collective Star Formation as a Contributor to Extragalactic Radio Sources

A. G. W. Cameron
GODDARD INSTITUTE FOR SPACE STUDIES
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

The strong radio sources appear to be the most energetic transient natural phenomena. Accounting for this energy is one of the most interesting aspects of the problem which they represent. G. R. Burbidge has found that the most likely source of the required large number of relativistic particles would be an outburst of supernova explosions. He found that in a given galaxy one would need $\sim 10^8$ to 10^9 Type I supernovae in $\sim 10^6$ to 10^7 years; that is, a huge increase over the usual rate of supernova activity in an ordinary galaxy. These requirements are impressive. However, Dr. Burbidge's hypothesis of a supernova chain reaction (described elsewhere in this volume) is not in accord with my ideas on the nature of Type I supernovae.

We recall that Type I supernovae are the fairly old stars with masses only slightly greater than the sun's, whereas stars of some five or more solar masses become Type II supernovae. There are also two means which have been suggested for attaining the necessary high rate of supernova activity: the chain reaction, which we might term "collective death," and the collective birth theory advocated in this paper. The rationale of the latter hypothesis can be outlined very briefly as follows: the life of a massive star is approximately the time required to convert the hydrogen core to helium; roughly speaking, such a star leaves the Main Sequence when half of the central mass is helium, but since the luminosity of heavy stars is proportional to the mass, the time required to evolve off the Main Sequence is mass-independent, and in fact is $\sim 3 \times 10^6$ years; the star then rapidly evolves to the supernova stage, which occurs by the implosion mechanism. Thus, massive stars formed simultaneously will become supernovae at roughly the same time. Next we will consider why simultaneous formation of such stars can be expected.

We envision star formation as beginning with a huge gas cloud of low density. The cloud becomes gravitationally unstable and the ensuing fragmentation leads to the development of individual protostars. The problem of how the cloud first becomes unstable is usually discussed in terms of the virial theorem

$$2U + M + \Omega + 2K_t < 0 \tag{1}$$

where

U = internal thermal energy
M = magnetic energy
Ω = gravitational potential energy
K_t = turbulent energy

and the inequality indicates that the system is gravitationally unstable. We will neglect the last term in (1) for reasons which are discussed below, and express the other quantities in a spherical coordinate system:

$$M^{2/3} > 17.8\, T\, \mathrm{n}_H{}^{-1/3} + 1.11 \times 10^{15} H^2\, \mathrm{n}_H{}^{-4/3} \tag{2}$$

In order to apply the relation (2) to the case of the giant elliptical galaxies in which the strongest radio sources seem to occur, we can take

$$\begin{aligned} T &= 100^\circ\ K. \\ H &= 10^{-6}\ \text{gauss} \\ \mathrm{n}_H &= 10^{-2}\ \text{cm}^{-3} \end{aligned} \tag{3}$$

then

$$M > 3 \times 10^8\, M_\odot \tag{4}$$

which is of the right order of magnitude to yield the number of supernovae that we require. One can vary the assumed parameters (3) quite a bit, but the *essential point* is that in giant elliptical galaxies the *magnetic energy* is the principal term which the gravitational potential must overcome in order to produce instability.

The form of the birth rate function is an open question. We would like to know, for example, whether the existence of the magnetic field as the limiting condition which determines the occurence of fragmentation might lead to the preferential formation of very massive stars. A better understood consequence of the predominance of the magnetic energy is its effect on the contraction of the gas cloud.

In the non-magnetic case, where the principal internal energy is thermal, the contraction of a gravitationally unstable cloud tends to take place isothermally. As the contraction proceeds, eventually (2) is satisfied for small subunits of the cloud and hence fragmentation occurs. But if the magnetic energy dominates the right hand side of (2), then the cloud contraction must be a cooperative phenomenon, because M increases proportionally to Ω, and hence no fragmentation would take place. This is the fundamental point of the theory of collective birth. Of course, eventually angular momentum effects would flatten the contracting cloud and the details of star formation in the resultant disc would be very complicated. One can imagine, for example, that the magnetic friction due to differential rotation might squeeze blobs of gas together along the lines of force. In these circumstances, the birth rate function could easily be drastically different from the normal one, in the sense that greater numbers of massive stars might be produced.

The contraction process, which may have a time scale much greater than that associated with the radio sources, should remain cooperative until the terminal stage, as shown above. The subsequent evolution time of Type II supernovae will be $\sim 3 \times 10^6$ years, roughly independent of mass for the larger stars, and hence the occurrence of the $\sim 10^8$ supernova explosions will be confined to an acceptably short interval of time.

Dr. Burbidge has pointed out that in some giant elliptical galaxies the gas at the center is considerably denser than the value assumed in (3), and that the $2K_t$ term will be dominant there. However, this great turbulence, if maintained over a sufficiently long period, will cause the local gas to disconnect itself from the magnetic field which pervades the rest of the galaxy. Thus the gas at the center of the galaxy would not participate in the contraction process which leads to collective star formation. The evidence for the highly turbulent central gas is based on the observations of Osterbrock, who in one case also found non-turbulent gas surrounding the central region, and it is this sort of gas which we have discussed above.

The central, turbulent gas can be regarded as being in a very deep potential well. There is actually an advantage, from the point of view of maintaining the cooperative contraction, in excluding this central gas from the contraction process, because the angular momentum which the contracting cloud must conserve can go into motion of its center of mass about the center of the galaxy.

On the present model, there should be localized regions near where maximum star formation occurs, where the magnetic field can attain values of $\sim 10^{-3}$ gauss or more. The injection of relativistic particles into such regions, when the supernovae occur, should lead to the emission of optical synchrotron radiation. Thus, the presence of optical jets which have been observed fairly close to the centers of a few strongly radio-emitting elliptical galaxies is accounted for.

This paper is concerned with the origin of the energetic particles responsible for the nonthermal emission of strong radio sources. Elsewhere in this volume, Drs. Woltjer and van der Laan discuss theories for the evolution of a radio source after this injection occurs and the fields and particles explode outwards from the central region of the galaxy. The present theory is essentially a basic scheme which needs to be elaborated in any given case because of local complexities which must arise, and therefore it deserves to be examined on its merits for the various individual sources.

DISCUSSION

G. R. Burbidge: The conditions assumed in (3) are identical to those attributed to the galactic halo by some workers. Therefore, we ought to observe star formation in the halo if this theory is correct.

Cameron: Strong radio sources do occur in the haloes of some spiral galaxies, and I would attribute these to precisely what you suggest. How general such a process can be in the haloes of spiral galaxies I do not know, since one must ask if shearing motions or circulation currents in the halo may disrupt the collective star formation process.

Woltjer: Adopting the parameters in (3) leads to an initial cloud radius of ~ 5 kiloparsecs. Therefore, a large contribution to Ω results from the gravitational attraction of the stellar mass of the galaxy. Doesn't this affect the possibility that the cloud will become gravitationally unstable?

Cameron: I assume this would modify the details of the process and may impose some lower limit on the gas densities required for gravitational instability. However, the general gravitational field of the galaxy may also be very helpful in that it will serve to trap and store the gas evolved as a result of stellar evolution until such time as the conditions required for gravitational instability are attained.

Schmidt: If this process in fact occurs, then the contribution of the supernovae should be comparable to the total luminosity of the galaxy. How many elliptical galaxies should have supernova-like spectra on this model?

Cameron: If 10^7 Type II supernovae go off in 10^6 years, and if each is near maximum luminosity for about a week, then it would still be very hard to see the supernova spectra in the spectrum of a giant elliptical galaxy. If the recurrence time of the collective star formation is 10^9 years, then only one galaxy in 1000 would be a candidate for such an observation.

Minkowski: It is now fairly certain that, contrary to our previous belief, a Type II supernova has the same visual absolute magnitude (~ -18) at maximum as a Type I. Baade discovered this in a new analysis of the existing supernova data which he performed during his last summer in Australia. He intended to write a paper on it when he was at Gottingen, but unfortunately he didn't, and the material has not yet been found among his effects. More recent observations, combined with redshift data, confirm this.

On the Interpretation of Faraday Rotation Effects Associated with Radio Sources

B. J. Burn and D. W. Sciama
KING'S COLLEGE
UNIVERSITY OF LONDON

1. INTRODUCTION

The discovery of Faraday rotation effects associated with the polarized radiation from radio sources has opened up an exciting new field of radio astronomy. Already there are data on about 20 sources, and more will presumably be forthcoming. These data should give us information on the distribution of free (thermal) electrons and magnetic fields both in the source itself and along the line of sight between the source and the observer. In this chapter we shall attempt to make a preliminary analysis of the present data. This analysis is of an exploratory nature, and our conclusions are quite tentative, but they do indicate the type of information that can be obtained. When the data become more precise and more extensive, an unambiguous interpretation should become possible.

2. THEORY OF FARADAY ROTATION EFFECTS

The basic formula for Faraday rotation in the radio region is the following:

$$d\theta = -8.1\,\lambda^2\, n\, \boldsymbol{H} \cdot d\boldsymbol{r}, \qquad (1)$$

where $d\theta$ is the angle of rotation of the direction of (linear) polarization relative to the observer in radians (taken positive for clockwise rotations), λ is the wavelength of the radiation in meters, n is the number of free electrons per cubic centimeter, $\boldsymbol{H}$ is the magnetic field in gammas (1 gamma $= 10^{-5}$ gauss) and $d\boldsymbol{r}$ is the distance traversed by the radiation in parsecs. The appearance of the scalar product of $\boldsymbol{H}$ and $d\boldsymbol{r}$ is a reminder of the fact that the sense of the rotation depends on the relative orientation of the magnetic field and the direction of propagation. The mixture of units used has the advantage that each quantity then has a reasonable value and the coefficient in (1) is also reasonable.

The observed Faraday rotation results from the superposition at the observer of all the elements of radiation, each of which traverses a different path. The general theory allowing for all possible complications is somewhat elaborate. In view of the preliminary and sketchy nature of the present data, we give a simplified version of the theory here. The essential point is that we need a formula not only for the direction of polarization as a function of wavelength, but also for the degree of polarization as a function of wavelength. The reason is that different elements of radiation suffer different wavelength-dependent Faraday rotations, so that when they are superposed the net polarization is also wavelength-dependent. This effect generally, though not always, leads to a *depolarization* which increases with wavelength (since the differential Faraday rotation, or Faraday dispersion, is larger then). There are other wavelength-dependent depolarizing mechanisms (listed below) but usually the Faraday mechanism is the most important in practice. Thus observations of the degree of polarization as a function of wavelength give us relevant information about the Faraday effect.

It is convenient to define a complex polarization P as $pe^{2i\alpha}$, where p is the degree of polarization and α is its direction. When incoherent elements of radiation are combined the resultant complex polarization is just the average of the individual polarizations, each weighted with its own intensity (Born and Wolf 1959). Now an element of synchrotron radiation has a degree of polarization

$$\frac{3\gamma + 3}{3\gamma + 7},$$

where γ is the electron energy spectral index (LeRoux (1961)). Then if γ is independent of position and frequency the observed polarization of a source is given by

$$P(\lambda^2) = \frac{3\gamma + 3}{3\gamma + 7} F^{-1} \iint I(\boldsymbol{r})\, e^{2i\{\alpha(\boldsymbol{r}) + \phi(\boldsymbol{r})\lambda^2\}}\, dr d\omega, \tag{2}$$

where the integration is over distance and solid angle, F is the total intensity, $I(\boldsymbol{r})$ is the intensity of the source at distance $\boldsymbol{r}$, $\alpha(\boldsymbol{r})$ is the direction of polarization of the source at distance $\boldsymbol{r}$ and

$$\phi(\boldsymbol{r}) = -8.1 \int_0^{\boldsymbol{r}} n\boldsymbol{H} \cdot d\boldsymbol{r}. \tag{3}$$

We shall call ϕ the *Faraday depth* of the point $\mathbf{r}$, in analogy with the term optical depth.

The integral in (2) can be simplified by combining all the radiation from regions with Faraday depth between ϕ and $\phi + d\phi$. Let the intensity of this radiation be a fraction $E(\phi)$ of the total intensity of the source and let its polarization be $p(\phi)e^{2i\alpha(\phi)}$ or $P(\phi)$. Then

$$P(\lambda^2) = \int_{-\infty}^{\infty} E(\phi)\, P(\phi)\, e^{2i\phi\lambda^2}\, d\phi. \tag{4}$$

Thus the observed polarization is the Fourier transform of a source function.* Since $P(\lambda^2)$ can be observed, it is tempting to invert this transform and so determine $E(\phi)P(\phi)$:

$$E(\phi)\, P(\phi) = \frac{1}{\pi} \int_{-\infty}^{\infty} P(\lambda^2)\, e^{-2i\phi\lambda^2}\, d(\lambda^2).$$

Unfortunately $P(\lambda^2)$ is not observable for $\lambda^2 < 0$, and so $E(\phi)P(\phi)$ cannot be derived uniquely from the observations.

We can, however, derive a unique source function $E(\phi)P(\phi)$ if we make the assumption that $\alpha(\phi)$ is actually independent of ϕ. This does not mean that all points in the source have the same direction of polarization, but only that all points at the same Faraday depth have an average direction of polarization which is the same for all Faraday depths. Since the direction of polarization at a point is determined by the direction of the magnetic field at that point, our assumption permits the field to have random fluctuations about a mean direction. Making this assumption and choosing $\alpha\,(\phi) = 0$, we see from (4) that $P\,(-\lambda^2)$ is just the complex conjugate of $P\,(\lambda^2)$. Hence

$$E(\phi)\, P(\phi) = \frac{2}{\pi} \int_{0}^{\infty} Re\,\{P(\lambda^2)\, e^{-2i\phi\lambda^2}\}\, d(\lambda^2),$$

which can be computed from the observations. Having obtained $E(\phi)\,P(\phi)$, the remaining problem is to use (3) to interpret it in terms of the structure of the source and of the intergalactic and interstellar medium between the source and the observer.

In practice the direction of polarization changes linearly with

*This result has been derived independently by many radio astronomers.

λ^2 for most sources. This behavior is not a general consequence of (4), and implies a limitation on $E(\phi)P(\phi)$. In fact we now have

$$P(\lambda^2) = r(\lambda^2)e^{2iA\lambda^2},$$

where $r(\lambda^2)$ is real and A is independent of λ. (Gardner and Whiteoak (1963) call A the *rotation measure* of the source, in analogy to the term emission measure.) Then

$$E(\phi)\,P(\phi) = \frac{2}{\pi}\int_0^\infty r(\lambda^2)\cos\{2(A-\phi)\lambda^2\}\,d(\lambda^2), \qquad (5)$$

which shows that this source function has to be symmetrical about $\phi = A$.

Finally, we consider other wavelength-dependent depolarizing mechanisms which may be important in particular cases.

(i) *The Beamwidth Effect*

This effect arises when the source is larger than the beamwidth of the telescope. The beamwidth changes with wavelength, and so the fraction of the source within the beam changes with wavelength. Unless the source is uniform across the beam this will lead to a net change in polarization. This effect occurs in Centaurus A and in optical surveys of the Crab Nebula (where the beamwidth is changed mechanically).

(ii) *The Spectral Effect*

If the radiating electrons have a different energy spectrum in different regions of the source, the relative weightings attached to each region will vary with wavelength. Again unless the source is uniform there will be a net change of polarization with wavelength. This effect may be important for double sources if the two components have different spectra.

(iii) *The Index Effect*

The degree of polarization depends on the electron energy index γ as $(3\gamma + 3)/(3\gamma + 7)$. If γ depends on the electron energy (curved spectrum), the basic polarization at each point changes with wavelength. This effect is not large for most sources, which have $2 < \gamma < 3$.

(iv) *The Bandwidth Effect*

There will be differential Faraday rotation within the bandwidth of the telescope, and this tends to depolarize the radiation. In practice this effect is usually small.

3. THE CRAB NEBULA

Polarization measurements on the Crab have been made over a wide range of wavelengths, so that a Fourier inversion is practicable. The direction of polarization changes linearly with λ^2, the rotation measure A being -27 rad. m^{-2}. We can therefore use equation (5). For the percentage polarization we take the following values:

optical	9.2%
3 cm	6.5%
10 cm	3.5%
15 cm	2.2%
21 cm	1.9%
30 cm	0.9%

The optical-radio depolarization can be accounted for in terms of the spectral effect. The required spectral index difference is only 0.04, which is of the order of the observed difference between the central regions and the outskirts (Woltjer 1958). We therefore consider two alternative models for $P(\lambda^2)$. The first assumes that all the depolarization is due to Faraday dispersion and the second that only the depolarization at radio wavelengths is due to this effect.

From the calculated value of $E\ (\phi)\ P\ (\phi)$ one can determine the fraction $F(\phi)$ of the radiation which has a Faraday depth less than ϕ. The results for the two models are as follows:

$\phi - A$ (rad. m^{-2})	$F_1(\phi)$	$F_2(\phi)$
1	0.04	0.05
3	0.10	0.14
10	0.28	0.41
30	0.47	0.65
100	0.75	1.00
300	0.79	
1000	0.89	
3000	1.00	

We see from this that a considerable fraction of the source has a Faraday depth an order of magnitude greater than the rest. This is a consequence of the fact that the polarization drops rapidly at first as the wavelength is increased and then has a long tail. This behavior is not what would be expected on the basis of a variety of simple models. One of us (B.J.B.) has calculated many such models, e.g. uniform sources of various shapes, sources with fluctuating magnetic fields and free electron concentrations, double sources, etc. None of these has such a large Faraday dispersion.

One possible explanation is that about half of the Crab lies behind ionized clouds with, say (for model No. 2) $n \sim 10\ \mathrm{cm}^{-3}$, $H \sim 4$ gamma and $r \sim 0.5$ pc. However, a more likely explanation is that the effect occurs in the filaments surrounding the central region of the Crab and covering a fraction of its surface area. Woltjer (1958) has suggested that these filaments contain electric currents flowing parallel to their axes. The magnetic field of these currents enables the internal force-free field to connect on to the external field. Because of the circular nature of the field due to the filaments it will give rise to as much Faraday rotation in one sense as in the other. Hence $E(\phi)\ P(\phi)$ will be symmetric, as is observed. For a bright filament we take $n \sim 1.5 \times 10^{3}\ \mathrm{cm}^{-3}$, $H \sim 30$ gamma, diameter $\sim 1''$, giving a Faraday depth of the right order.

4. EXTRAGALACTIC SOURCES

Data are available at too few wavelengths to justify a Fourier inversion. An attempt to fit simple models to the data shows that many sources are like the Crab in that the polarization at the longer wavelengths is greater than would be expected. In these cases there are again the two possible explanations. The possibility that the sources are partly covered by ionized clouds would be supported by the apparent correlation between the galactic latitude of a source and its amount of depolarization (Gardner and Whiteoak (1963)). At the present time the evidence for this correlation is not very strong. The other possibility remains, namely that the sources are surrounded by a filamentary structure similar to that of the Crab. This is reasonable in that current views suggest that the strong radio sources are, like the Crab, the result of an explosion occurring within a magnetized medium. We favor this second explanation.

A final point worth mentioning is that in the case of Centaurus A, the first extragalactic source in which Faraday rotation effects were detected (Cooper and Price 1962), the observed rotation of roughly $-60\ \mathrm{rad/m^2}$ may be mainly due to effects occurring outside the source. The evidence for this is that, as pointed out by Cooper and Price, the rotation measures along three different lines of sight have only a small dispersion. If the internal effect makes the main contribution to the rotation measure, then the source must be uniform over a distance of order 160 kpc. On the other hand, if the effect is external it is occurring nearer to us, so that the required uniformity need not have such a large scale.

Various proposals have been made as to where the effect is mainly occurring. The two most likely places seem to be an ionized galactic cloud with $n \sim 10\ \text{cm}^{-3}$, $H \sim 1$ gamma, $r \sim 1$ pc, and the local group of galaxies (Sciama 1962 a,b) with $n \sim 3 \times 10^{-4}$ cm^{-3}, $H \sim 5 \times 10^{-2}$ gamma, $r \sim 10^{6}$ pc. A decision between these two hypotheses will have to be based on a statistical study of the dependence of rotation measure on the direction of a source. More data than are now available will be required for this task.

A detailed account of these calculations will be published elsewhere by one of us (B.J.B.).

REFERENCES

Born, M. and E. Wolf (1959), *The Principles of Optics,* Pergamon.

Cooper, B. F. C. and R. M. Price, (1962), *Nature 195,* 1084.

Gardner, F. F. and J. B. Whiteoak (1963), *Nature 197,* 1162.

LeRoux (1961), *Annales d'Astrophysique 24,* 71.

Sciama, D. W. (1962a), *M.N.R.A.S. 123,* 317.

——— (1962b), *Nature 196,* 760.

Woltjer, L. (1958), *B.A.N. 14,* 39.

A Model of Radio Galaxies

H. van der Laan
MULLARD RADIO ASTRONOMY OBSERVATORY
CAVENDISH LABORATORY

INTRODUCTION

Theoretical discussions of radio galaxies have been limited by the lack of reliable data for a sufficiently large sample of sources. Some of the models which have been proposed turn out to be based on spurious correlations or apparent uniformities of certain parameters, which arose from the poor statistics of small samples. But recently, complementary programs of various radio observatories have yielded considerable essential information for a large number of individual sources. These data, combined with redshift determinations of an increasing number of identified sources, now provide absolute values of source parameters for quite a large sample of radio galaxies.

Before outlining the model of radio galaxies it is necessary to consider the data on which it is based. Since much of this material is presented in detail by other contributors to this report, a very brief review of those aspects directly relevant to the theory will suffice.

OBSERVATIONAL DATA

(i) *The radio spectra*—The data from the work by Conway, Kellermann and Long (1963), are summarized by Dr. Conway in this report; we follow his notation. These results show that nonthermal radio sources have a variety of spectral characteristics. Plotting flux density against frequency on logarithmic scales, it is found that most sources have spectra which are remarkably straight between 38 and 1420 Mc/s. These are designated as spectral type S. About ten percent of all sources in a sample complete above a given flux density have spectra which depart significantly from linearity in this frequency range and are classified as type C. Where the data are sufficient, the type S sources are subdivided into categories S–1 and S–2; the former have spectra which remain linear up to 3200 Mc/s while for the latter the measured flux density at this frequency is significantly less than that given by an extrapolation of the 38 — 1420 Mc/s line. The only correlation between spectral type and other source characteristics which was found is that of curved (type C) spectra and high brightness temperatures (Kellermann *et al.*, 1962).

Without going into the detailed implications here, it is already clear from these data that the process which generates the relativistic electrons gives them an inverse power law of differential energy distribution. The exponent of this distribution, which in a sample of sources varies over a small range, in any one source remains constant during the whole generation period. If this were not so, some sources would have concave radio spectra; but all observed spectra are either straight or convex. The observed curvature is therefore to be explained in terms of electron energy losses.

As is well known, synchrotron losses steepen the radio spectrum, starting at high frequencies. For a source of constant magnetic field strength B, the frequency ν_c at which the "synchrotron loss bend" occurs is related to the age of the source by

$$t \sim 26\, B^{-3/2}\, \nu_c^{-1/2}.$$

The relation between sources with type C and type S spectra which first suggests itself is that where for the former 40 Mc/s $\lesssim \nu_c \lesssim$ 3000 Mc/s while (since type C sources tend to be stronger and have higher brightness temperatures) type S sources are older, having evolved through the type C stage and now have $\nu_c < 40$ Mc/s; *i.e.* the curvature has moved below the observed frequency range. This course of events is tentatively suggested in the CKL paper and seems implicit in the models of Shklovsky (1960, 1962) where a source such as Cygnus A evolves to become a more extended source such as Hercules A.*

The implications of this assumption are the following: if $B \sim 10^{-5}$ gauss then $\nu_c < 40$ Mc/s means $t_s > 10^8$ years. Since ~ 10 percent of all sources in a sample complete above a given flux density have type C spectra, it follows that this evolutionary pattern requires $t_s > 10^9$ years, a value which increases still further when it is recognized that type C sources tend to be stronger than type S or if $B < 10^{-5}$ gauss. In addition, since this model requires the spectrum to be straight at frequencies above the synchrotron loss

*This evolutionary assumption was also forwarded by the author at the conference.

bend, the generation of relativistic electrons must continue during the entire lifetime of the source, because synchrotron losses, which under *these* conditions increase the spectral index by 0.5, make the spectrum arbitrarily steep when particle injection stops.

For reasons of stability (see below), $B \not> 10^{-5}$ gauss; so this hypothesis requires $t_s > 10^9$ years. It can be shown, as discussed below, that such long time scales are ruled out for dynamical reasons. This evolutionary sequence is untenable.

The alternative is $\nu_c \gtrsim 3000$ Mc/s for type S sources. If the magnetic fields in these sources are comparable to or less than the equipartition values (Maltby, Matthews and Moffet, 1963) then $t \sim 10^7$ to 10^8 years. The frequency ν_c, if in the observed range, can then be used as a datum in a dynamical theory.

(ii) *Brightness distributions*—Important studies of the brightness distributions in radio galaxies have been completed at Nancay (Lequeux, 1962) and the California Institute of Technology (Maltby and Moffet, 1962). The CalTech results are given by Dr. Moffet in this report.

There are at least two alternative approaches in dealing with these data. One is to regard the observed brightness distribution as a reflection of the magnetic intensity distribution in the space surrounding the optical galaxy prior to the radio emission phase (Woltjer, 1962 and this report). Another is to consider the interaction of the relativistic gas which escapes from the optical galaxy after the initial energy releasing event with the external medium, assumed uniform, to see whether this disturbance can give rise to the observed brightness distributions. The latter method is outlined in the last section.

(iii) *Angular diameters*—The very long baseline interferometer observations carried out by the Jodrell Bank group (Allen *et al.*, 1962) provide valuable information about angular size and structure for a large fraction of 3C sources. These data yield estimates of the brightness temperatures of a major component within many of these sources. Out of 160 sources at $|b| > 10^\circ$ for which the visibility curves are sufficiently complete, sixteen have brightness temperatures above 2×10^7 °K at 400 Mc/s (Long, 1962). That is, about ten percent of all sources in a complete sample have brightness temperatures comparable to or in excess of that of Cygnus A. In view of the correlation between spectra and high brightness temperatures, this estimate is consistent with that made in (i),

$$N_c/N_s \sim 0.1.$$

(iv) *Polarization*—As reported by a number of observers, a linearly polarized component has been detected in the radiation from many extragalactic sources. These measurements indicate that the magnetic fields in these sources possess large scale regularity. Polarization angles determined at several frequencies and extrapolated to infinite frequency enable the true position angle, and hence the mean projected direction of the magnetic field, to be derived. In addition, the decrease in percentage polarization from a short to a relatively long wavelength, if attributed to differential Faraday rotation in the source, provides an estimate, albeit crude, of the product $\overline{nB_{\parallel}}$ in the source. Both this quantitative datum and the qualitative information of projected magnetic field direction are evidently useful in the formulation of a theory of radio galaxies.

(v) *Optical identifications*—The identification of radio sources with optical galaxies is the only means of determining their distances and hence the absolute values of the radio source parameters. These are essential for any theoretical discussion and for the construction of the radio galaxy luminosity function (Dr. Minkowski; this report). But these aspects need not be discussed here.

If particles escape from the optical galaxy in preferred directions then some relation between its orientation and that of the extended radio source is to be expected (Shklovsky, 1960). No such relation is found when radio brightness distributions are superimposed on optical photographs (see Maltby, Matthews and Moffet, 1963). Suppose the radius of a simple component in a double galaxy is r and the separation of the two components is $2R$, and that the duplicity of many radio galaxy brightness distributions is to be explained by the passage of relativistic electrons, which escape isotropically from the optical galaxy, through two magnetic field concentrations which were present prior to the energy releasing event. Then all but a fraction $\sim r^2/2R^2$ escape without radiating at all, raising the already severe energy requirements by another order of magnitude.

A THEORETICAL MODEL

The problem posed by the energy requirements of extragalactic synchrotron radiation sources has been a prominent one for a decade and cannot be said to have been satisfactorily resolved even now. If it is assumed that both the initial energy releasing event and the process which converts this energy, whatever its form, into a flux of relativistic particles with the required energy distribution, are completed in a time T which is short compared to t, the age of the radio source, then the evolutionary phase can be discussed without detailed knowledge of the initiating process. Some hypotheses concerning the latter (Burbidge, 1961; Hoyle and Fowler, 1963) meet these conditions. The radio spectrum of Cygnus A is also most naturally explained in terms of synchrotron losses with $T << t$, for its spectral index increases by rather more than 0.5 from low to high frequencies. If sources such as 3C 48 and 3C 273 are extragalactic (*e.g.* Schmidt, 1963) then in these sources relativistic particle fluxes of total energy comparable with those in the large strong radio galaxies exist in regions at most a few kiloparsecs in diameter. Their exceedingly high energy density makes such systems very unstable so that to exist at all such sources must have been generated over a very short period.

The idealized problem then reduces to the following: a relativistic gas, of a certain energy distribution and total energy, expands spherically from an initial volume of, say, galactic dimensions, into the extragalactic medium. The magnetic field of the medium couples the motion of the relativistic gas with that of the medium's thermal gas. If the initial total energy is sufficiently large then the rate of expansion is initially supermagnetosonic and a shock front separates the undisturbed medium from the expanding region.

The essential unknowns of the problem are: n_o, the medium's hydrogen number density; B_o, the medium's magnetic field strength; E_i, the total initial energy of the relativistic gas (related to the energy at radius r by $E = E_i r_i / r$); τ, the ratio of the total energy carried by the relativistic particle flux to the energy of its electron component; and a parameter β, which is a measure of the instantaneous speed of expansion or, equivalently, of the age of the expansion.

Five independent relations are required, which are provided by:

(i) the dynamics of the expansion; the solution of the equation of motion relates t with n_o and E_i and with the radius r, a measurable quantity;

(ii) the synchrotron emission theory, which relates the measured power of the source with E_i, τ, B_o and r;

(iii) the change of polarization with wavelength, which gives the product $\overline{nB_{\|}}$, as discussed above, whence $n_o B_o$ can be obtained;

(iv) the theory of radio spectral curvature, yielding a relation between t, B_0 and the measurable value of ν_c;*

(v) a stability condition, requiring the medium external to the energy-releasing galaxy to be gravitationally stable; this requirement relates the ratio n_0/B_0 with the radius of this region, which is at most of the order of a cluster radius.

The theory can be applied only where the observable parameters are known. Numerical solutions have been obtained for four well explored sources. These are given in the table; $\tau \simeq 10$ for all four sources.

	3C 327	Her A	Cyg A	3C 353
B_0 (gauss)	3×10^{-6}	7×10^{-6}	2×10^{-5}	8×10^{-6}
n_0 (cm^{-3})	3×10^{-4}	3×10^{-4}	9×10^{-4}	5×10^{-4}
E (ergs)	7×10^{59}	2×10^{60}	2×10^{60}	7×10^{58}
t (years)	6×10^{7}	3×10^{7}	5×10^{6}	3×10^{7}

When the speed of expansion has decreased to the Alfven speed in the undisturbed medium the source loses its identity as the fast particles escape into the surrounding space. This gives upper limits for the age and the dimensions of the source. These lifetimes turn out to be intermediate between the lower limit L/c, where L is the linear scale of the source, and a sort of upper limit E/P, where E is the minimum total energy in the source calculated using conventional equipartition assumptions (*cf.* Maltby *et al.*, 1963), and P is the power emitted in the radio frequency range.

The lack of spherical symmetry in radio galaxy brightness distributions can be attributed to an anisotropic property of the medium, namely a magnetic field which is fairly regular and unidirectional on a scale comparable with the dimensions of the sources ($\sim$ 100 kpc). Under these conditions the theoretical brightness distributions are consistent with the interferometric data. In this model, halo and double sources are physically similar, but differently oriented with respect to the observer.

Halo sources are not expected to have any net polarization. In double sources, expected to be substantially polarized, the projected magnetic field direction should be normal to the line joining the two components where these are symmetrically located relative to the optical galaxy. In case of marked asymmetry, probably due to density variations in the medium, the position angle is more uncertain.

*Adiabatic expansion losses also shift the curvature down the frequency scale, but although this is an important mode of energy loss, it is important only during the first fraction of a source's lifetime. For large t the value of ν_c is therefore determined by synchrotron losses.

The theory suggests that radio galaxies of large linear dimensions must be associated with clusters where there are a relatively strong magnetic field ($\sim 4 \times 10^{-6}$ gauss) and high intergalactic mass densities ($n_H \sim 5 \times 10^{-4}$ cm^{-3}).

The detailed development of the model and a fuller discussion are given elsewhere (van der Laan, 1963 a,b).

REFERENCES

Allen, L. R., B. Anderson, R. G. Conway, H. P. Palmer, V. C. Reddish and B. Rowson (1962), M.N.R.A.S. *124*, 477.

Burbidge, G. R. (1961), Nature *190*, 1053.

Conway, R. G., K. I. Kellermann and R. J. Long (1963), M.N.R.A.S. *125*, 261.

Hoyle, F. and W. A. Fowler (1963), Nature *197*, 533.

Kellermann, K. I., R. J. Long, L. R. Allen and M. Moran (1962), Nature *195*, 692.

van der Laan, H. (1963a), M.N.R.A.S. *126*, 519.

———(1963b), M.N.R.A.S. *126*, 535.

Lequeux, J. (1962), Ann. d'Astrophys. *25*, 221.

Long, R. J. (1962), private communication.

Maltby, P. and A. T. Moffet (1962), Ap.J. Suppl. *7*, 93-164.

Maltby P., T. A. Matthews and A. T. Moffet (1963), Ap.J. *137* 153.

Schmidt, M. (1963), Nature *197*, 1040.

Shklovsky, I. S. (1960), Astron. Zhur. *37*, 945.

———(1962), Astron. Zhur. *39*, 591.

Woltjer, L. (1962), Ap.J. *136*, 1152.

Dynamics of Magnetic Fields in Radio Sources

L. Woltjer
DEPARTMENT OF ASTRONOMY
COLUMBIA UNIVERSITY

The most important problems in the theory of radio sources are (1) the energy supply and (2) the dynamics of the magnetic fields. The question of the energy supply has been extensively discussed and is still unsolved; I will not discuss it in this paper. I believe that the discussion of the magnetic fields may prove even more difficult. If energy is available, it is possible to visualize acceleration mechanisms for relativistic particles; but it is much harder to produce a magnetic field, because of the conservation of flux in a good conductor.

The question of the magnetic fields will be discussed from two points of view:

(a) The radio spectra
(b) The Faraday effect

The results on the Faraday effect are based on polarization observations which may still be somewhat uncertain. However, my remarks will be confined to Cygnus A, for which Dr. Mayer has obtained a beautiful set of polarization data. It seems unlikely that these will need significant revision because of future work.

Let us first look at the question of the spectra in connection with the various models which have been discussed for the extragalactic sources. To begin very simply, let us assume a closed stationary magnetic field, which confines all the relativistic particles that have been suddenly injected into it. Since the particles can't escape, such a source can radiate for a rather long time. But gradually the particles of higher energy begin to die out, since the synchrotron losses go as E^2. Therefore, after some time, although the spectrum would not have changed very much at the lower frequences, it would begin to bend down at the higher frequencies. If continuous injection of particles is assumed, there is a somewhat less extreme situation, but still there is some bending down of the spectrum.

Dr. Conway reported earlier in this conference the evidence for a bending down at about 3000 Mc/s in the spectra of some radio sources. I think there is fairly general agreement that for most sources the cutoff is situated at or above this frequency, unlike the case of Cygnus A. However, on the basis of the simple model discussed above, there should be about three times as many sources with spectra curved like that of Cygnus A as sources with spectra which are straight to 3000 Mc/s. Therefore the model of a closed, stationary magnetic field must be rejected.

The second model which we will consider is one in which, although there is also a stationary magnetic field, the particles can escape. If the escape is independent of energy, and if there is instantaneous injection, one would expect the older sources to be not only fainter at the higher frequencies, but also systematically weaker at all frequencies. But then there is less chance of observing an older source because intrinsically faint objects can only be detected in a limited volume of space, and therefore if one chooses the time scale of the escape process to be of the same order as the time scale for energy loss by synchrotron radiation for the high energy particles, there wouldn't be much problem in reconciling the present observations with the model.

A third type of model is that which involves an expanding magnetic field. Such a type of model has been discussed, for example, by Shklovsky. One imagines a strong magnetic field limited originally to a small region of a galaxy. The field is blown up like a balloon and eventually occupies the huge volume which is observed for some radio sources.

There are serious limitations to this model, however. If one has an expanding object, then the magnetic field was stronger in the past, since the field strength

$$B \sim \frac{1}{r^2}.$$

Therefore, in such an object the synchrotron losses were greater in the past. Secondly, there is the effect of the adiabatic decompression of the expanding relativistic gas. The "temperature" of the gas, and hence the particle energy, is reduced, so that we have a second type of energy loss.

If one assumes instantaneous injection, then the maximum cutoff frequency in the spectrum of a source would vary as

$$\nu_{\max} \sim \left(\frac{1}{B^3t^2}\right) \frac{1 + \frac{5}{4}\theta}{x^6(\theta x^2 + x + 1)^2}$$

where

B = magnetic field strength

t = source age

$x = \dfrac{\text{present radius}}{\text{original radius}}$

It is assumed that the expansion proceeds in a spherically symmetric way. The parameter θ is zero in the conventional model where the electron momenta are taken as randomized. On the other hand, if the expansion proceeds very smoothly, so that all the magnetic moments are conserved, then $\theta = 1$.

If you take a plausible value for B and adopt $\sim 10^6$ years for t, since the time scale cannot be very short for a large source, then you find that values of x, the expansion factor, larger than two or three would lead to an observable cutoff in the spectrum.

Of course, while the source expands its intensity decreases at all frequencies, because the energy of all the particles is decreased by the expansion. So I think that the statistical argument that not many such cutoffs are observed is not relevant. But at least for the sources which are observed, upper limits to the expansion factor can be derived. For some typical sources, one finds that an expansion factor greater than 2 or 3 would be rather unlikely. Shklovsky, I believe, pointed out that if you expand Cygnus A it will resemble Centaurus A. The relativistic particle content is fixed, and the intensity is decreased by the expansion. However, the expansion of Cygnus A by a factor of 6 would cause the region of the spectrum in which the radiation is effectively emitted to fall at much too low a frequency.

Another model, for which Dr. Burbidge has expressed some sympathy, is one in which the particles are produced in a galaxy, but radiate in the intergalactic magnetic field. This has the advantage that the problem of the origin of the field can be left to the cosmologist, and that an expansion of the field to large volumes is not required. However, by definition an intergalactic field exists everywhere; so one has the difficulty that the particles cannot escape to a region of no magnetic field. By consequence, the model is essentially the same as that in which a closed and static magnetic field is assumed. The particles are injected into this field and gradually diffuse outwards; the energy loss of the particles is due only to synchrotron radiation. If the energy loss of the particles is in fact caused by synchrotron radiation, then the "death" of the radio source is accompanied by the arrival of a cutoff in the observable range of the spectrum.

G. R. Burbidge: This assumes that you have a constant field everywhere.

Woltjer: It becomes somewhat of a question of semantics as to what is a galactic field and what is an intergalactic field, if you consider that the intergalactic field is very much enhanced near a galaxy. Then a sufficient gravitational binding energy to keep this strong field near to the galaxy is required.

It thus is my impression that models involving very great expansion are unlikely to apply to most radio sources. Probably they thus have more or less stationary magnetic fields, from which particles are eliminated by escape. It is sometimes argued that a field in a volume as large as that of Hercules A can hardly be understood if it had not expanded from a much smaller region. But this requires a much greater initial field in the smaller region. It seems to me that the origin of the very strong field poses an equally difficult problem.

Let us now turn to the Faraday effects. These are of two types. First, there is a rotation of the plane of polarization. It is still uncertain as to whether this occurs in our own galaxy, in the radio source galaxy, or somewhere in between. Secondly, there is the depolarization caused by differential Faraday effects across the source. In the case of Cygnus A, Dr. Mayer and his associates at N.R.L. have shown that the polarization is 8% near 3 cm but is well below 1% near 9 cm. The source has a diameter of about a minute of arc. Apparently in different regions there are different amounts of Faraday rotation, so that the polarization of the whole source is reduced.

One might think that the depolarization could occur in the halo of our galaxy, rather than in the Cygnus A source. Very small scale irregularities in the galactic halo would be required, and when you consider the problem quantitatively, it seems difficult to get the observed large depolarization within a minute of arc beam. Therefore let us assume that the depolarization takes place in the source itself. This still leaves a number of possibilities; for example, the depolarizing region may be a shell around the source, or the depolarization may occur in a medium which pervades the source. In typical cases, if the total Faraday rotation along a line of sight through the source is Ψ, the degree of polarization will go as

$$\frac{\sin \Psi}{\Psi} \text{ or } \frac{\sin 2\Psi}{\Psi}$$

or a somewhat similar expression. The exact form depends on the assumed model.

Let us assume a relation of this type between the degree of polarization and the total Faraday rotation through the source. The observations of Cygnus A reveal that between the wavelengths of 3 cm and 9 cm, the depolarization amounts to a factor of 8 at least. The absolute value of the Faraday rotation increases by a factor of about 9 over this wavelength interval. At 9 cm, Ψ has to be at least a radian or so. One can then calculate from Ψ the integral

$$\int B_{\parallel} N_e \, dl$$

along the line of sight, and find N_e.

The result for the two lobes of Cygnus A assuming $B_{\parallel} = 3 \times 10^{-6}$, and 35 kiloparsec diameter (measured at CalTech), is that several times 10^8 solar masses of ionized gas are required to account for the polarization observations.

Faraday rotation is of particular interest in that it is one of the few observed quantities which depend on $\overline{B}$ rather than B^2. In particular, it depends on the component of $\overline{B}$ in a given direction along the line of sight, and therefore one can perhaps differentiate between small scale fields and large scale fields, since in the latter $\overline{B}$ has a systematic orientation over a large volume.

The mass of gas in Cygnus A that we have estimated from the polarization data can be compared with the mass which follows from a dynamical argument. We indicated that the source may not have expanded much (if the injection was instantaneous), which brings us back to the difficulty of how the magnetic field was produced. The simplest possibility may be that the field is primeval. Since we are not usually worried about the origin of the matter in the universe, we might likewise not be concerned about the origin of magnetic flux. In fact, they may have come into being simultaneously.

If we then suppose that the magnetic field is a permanent feature of the source, we have to require that the system have negative energy, that is:

$$\frac{L^3 B^2}{8\pi} < \frac{GMM_g}{L}$$

(L is the length scale, M the mass of the galaxy, and M_g the mass of the gas.) Taking a field of 3×10^{-6} gauss, and adopting a value of M, corresponding to a mass-to-light ratio of 50, we find that the minimum amount of gas required to anchor the field lines in the galaxy is

$$M_g = 1.3 \times 10^9 \, M\odot$$

which is of the same order of magnitude as that calculated by the polarization argument.

If we reverse the argument, then given the negative energy of the source and the observed Faraday rotation, we calculate a value of about 5×10^{-6} gauss for the magnetic field of Cygnus A.

Applying these calculations to various other sources, using the data by Gardner and Whiteoak, we find values typically of 0.5 to 5 microgauss.

From the preceding arguments, we conclude that the magnetic fields in radio sources could be permanent features of the associated galaxies. Normally, such a field will not be observable, but if a large amount of energy is released in the form of relativistic electrons, the region of the field will "light up" and become a radio source. Of course, one must then amend our previous considerations of dynamical balance to take account of the kinetic energy of the particles, which may exceed the magnetic energy by a factor of the order of 10 to 30. Thus the total energy of the system may become positive, and the radio source will expand. But after some time the particles are lost by escape and perhaps it is even possible that the configuration eventually returns to its original state.

DISCUSSION

Conway: As I understand it, in your various models the spectral cutoff is regarded as a sign that the source is just about dead. Do any of the theories explain the correlation between high brightness temperature and the spectral cutoff?

Woltjer: No.

van der Laan: How does your model account for the variety of observed brightness distributions such as double sources, core and halo sources and so forth?

Woltjer: This may depend on the magnetic structure in galaxies.

G. R. Burbidge: Even more, you could use the argument that there is no unique amount of energy injected in a given event.

Matthews: What value did you use for the mass of the galaxy in this discussion?

Woltjer: I used a mass-to-light ratio of 50 and a Hubble constant of 100 km/sec Mpc. Then the mass of Cygnus A is near 10^{12} $M_\odot$.

Roberts: Why does one have to have gas in the extended region of the magnetic field in order to hold the field to the galaxy? For example, surely one can have a dipole field.

Woltjer: Yes, one could also have the gas in the galaxy. But from consideration of the Faraday depolarization, one requires the gas to be in the lobes of the source. I can't see how with any plausible parameters one can get sufficient depolarization from our galactic halo or disc in a one minute of arc beam at $\lambda \approx 5$ cm. One needs to get a difference of the order of a few radians over the one minute beam.

Radhakrishnan: Doesn't the depolarization depend on the scale of the inhomogeneities as compared with the size of the polarized region projected on the source? How do you get the actual value of the magnetic field from the fact that it drops from 8 percent at $\lambda = 3$ cm down to less that 1 percent at 10 cm?

Woltjer: We have adopted the assumption that the magnetic field has a large scale, of the order of 10 kiloparsecs. If you assume a small-scale (e.g., 10^2 parsecs) field, you need more gas to get the depolarization.

Radhakrishnan: What if the polarization of Cygnus A originated in just one of the two lobes, or perhaps something even smaller than that?

Woltjer: If it came from one of the regions then the argument applies only to that one lobe which would then have 20 percent intrinsic polarization. One cannot restrict the polarization to too small a region because you observe 10 percent polarization for the whole source, while the intrinsic radio polarization can't exceed 75 percent.

Moffet: What would be the time scale for the escape of relativistic particles?

Woltjer: It would be given by the synchrotron time scale for the highest energy particles present in the source. So if one has a cutoff at 10,000 Mc/s, then the time scale would be given by the lifetime of the synchrotron particles which radiate at 10,000 Mc/s. It would be of the order of a few million years.

Concluding Remarks

H. C. van de Hulst
UNIVERSITY OF LEIDEN
STERREWACHT, LEIDEN

Dr. G. Burbidge has already given a fine summary of the theoretical situation in this field, to which I would like to add one comment. In 1958, V. A. Ambartsumian suggested that some of the phenomena observed in the extragalactic radio sources pointed to the existence of still unknown laws of nature. It does not yet seem possible to prove or disprove this suggestion.

My overall impression of this conference calls to mind what someone has written about present-day chess matches: not only has the style of chess changed somewhat, but also its level has increased enormously; the champions of yesterday would not even be admitted as contestants in contemporary tournaments. I think that it is good occasionally to hold highly expert symposia, such as the present one, in which the speakers are not obliged to explain the background material to a general audience. However, this aggravates the problem of the diffusion of the scientific knowledge presented at such meetings. The organizers of the present conference appear to have been quite successful in getting together the principal workers of the relevant fields, but it is difficult to determine exactly who is interested and working in a given field. The unfortunate situation is that often one hears results discussed as "old stuff," but when inquiry is made as to the source of this obsolete material, we are informed that it has not been published yet! References to unpublished material are becoming common, but not, I think, popular. I feel that a responsibility rests on the organizers of science, that is, the people who sit on the councils of international unions and the editorial boards of journals, to keep this situation under control in some way.

There may also be implications for the teaching of graduate students. In order to be prepared for a meeting such as this one it is necessary to be familiar with such diverse subjects as nuclear physics, practical radio astronomy, and hydromagnetics, and also with "old-fashioned" astronomy. Not only spectroscopy, but even the determination of parallaxes and proper motions was discussed briefly! Certainly the reports presented during the last two days have underlined the fact that radio astronomy would be nearly at a dead-end without the collaboration of the optical observers in such things as identifying sources and performing subsequent optical studies. Please remember that it is only some nine years since Baade and Minkowski made the first optical identification of an extragalactic radio source.

The material presented here has been, in large part, extremely fresh. One speaker's slide illustrated observations made on 28 October 1962, and we have also seen a number of the results just obtained with the Parkes radio telescope. The value of the data taken with the newest antennae has demonstrated the importance of the statement that what radio astronomy needs, and will continue to need, is better angular resolution. An interesting point, however, which was not so clearly brought out during the conference, is that some cosmological studies have indicated that perhaps half of all extragalactic radio sources will never be identified because they are far beyond the limits of optical detection.

On the observational side, the fine interferometer studies and the polarization investigations reported at the conference impressed me most. As to the theoretical work, it seems clear that further progress is still necessary on the development of a realistic general model for the extragalactic sources, despite the fact that several quite detailed theories have already been advanced to explain particular aspects of the observations, such as the curvature in some source spectra.

Index

INDEX

☆ U.S. GOVERNMENT PRINTING OFFICE: 1964—O 740–350